Naval Facilities Engineering Command

ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

TECHNICAL MEMORANDUM

TM-2410-ENV

Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct-Push Technologies

By

William Major, Mark Kram, Louise Parker, Tim McHale, and Joel Michelson

June 2009

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0811*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
30 April 2008	Final	January 2000 to April 2008

4. TITLE AND SUBTITLE
Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct-Push Technologies

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
William Major, Mark Kram, Louise Parker, Tim McHale and Joel Michelson

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSES
NAVFAC Engineering Service Center
1100 23rd Ave, Port Hueneme, CA 93043

8. PERFORMING ORGANIZATION REPORT NUMBER
TM-2410-ENV

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
901 N. Stuart St., Suite 303, Arlington, VA 22203

10. SPONSOR/MONITORS ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
An ESTCP sponsored multi-site Long-Term Monitoring (LTM) project has been conducted to determine whether there is significant statistical difference between groundwater monitoring results obtained from direct-push and conventional hollow-stem auger installed wells. Five field sites are included in the study to represent a variety of geologic conditions as well as a cross-section of regulatory domains (e.g., EPA regions and states). Direct-push wells have been installed adjacent to, in well pairs or clusters, existing hollow-stem auger drilled wells at the following facilities: the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) in Hanover, NH; Dover National Environmental Technology Test Site at Dover AFB, DE; Port Hueneme National Environmental Technology Test Site at Naval Base Ventura County, CA; Tyndall AFB, FL; and Hanscom AFB in MA. Thirteen sampling events over a five year period (Phase I & II) have been completed at the sites in which groundwater samples have been analyzed for parameters typically examined with long-term site compliance monitoring including chemical concentrations, oxidation-reduction potential (ORP), pH, temperature, conductivity, turbidity , and dissolved oxygen (DO). The target analytes for this project include: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-DCE), trans-1,2-dichloroethne (trans-DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, o,m-xylene, p-xylene (the BTEX compounds), 1,4-dichlorobenzene (DCB), trichloroethane (TCA), and methyl tertiary-butyl ether (MTBE). Analysis of Variance (ANOVA) statistical methods have been employed to address a wide range of inherent variables such as well depth, screen length, filter packs, annular sealing, spatial and temporal heterogeneity, groundwater seasonal changes, plume characteristics, and geological conditions. Inorganic data was also collected on an annual basis to assess the performance of the direct-push well for monitored natural attenuation at the five test sites. Additionally, the ESTCP LTM project team partnered with the ITRC Sampling, Characterization and Monitoring (SCM) team to product a Direct-Push Well Technology Technical/Regulatory Guidance Document and internet training module.

15. SUBJECT TERMS
Direct-push well technology; hollow-stem auger; drilled wells; well performance comparison; long-term monitoring, well pairs; well clusters; organics; inorganics; analysis of variance; statistical methods; ITRC; LTM; groundwater contaminants

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES 153	19a. NAME OF RESPONSIBLE PERSON
U	U	U		317	William R. Major
					19b. TELEPHONE NUMBER *(include area code)* 805-982-1808

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Environmental Security Technology Certification Program

(ESTCP)

Final Report

Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct-Push Technologies
CU-0011

NAVFAC ENGINEERING SERVICE CENTER
PORT HUENEME, CA

COLD REGIONS RESEARCH ENGINEERING LABORATORY
HANOVER, NH

AIR FORCE RESEARCH LABORATORY
WEAPONS SYSTEM LOGISTICS BRANCH
TYNDALL AFB, FL

UNIVERSITY OF CALIFORNIA
DEPARTMENT OF GEOGRAPHY
SANTA BARBARA, CA

APPLIED RESEARCH ASSOCIATES, INC.
SOUTH ROYALTON, VT

April 2008
Approved for public release; distribution is unlimited.

KEY ACRONYMS

AFB	Air Force Base
AFRL	Air Force Research Laboratory
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BGS	Below Ground Surface
BTEX	Benzene, Toluene, Ethyl Benzene, Xylene
CFR	Code of Federal Regulations
CPT	Cone Penetrometer Test
CRREL	Cold Regions Research and Engineering Laboratory
DNAPL	Dense Non-Aqueous Phase Liquid
DNTS	Dover National Technology Site
DO	Dissolved Oxygen
DoD	Department of Defense
DOE	Department of Energy
DP	Direct-Push
EPA	Environmental Protection Agency
ERDC	Army Corps Engineering Research and Development Center
ESTCP	Environmental Security Testing and Certification Program
ETV	Environmental Technology Verification
GC/MS	Gas Chromatography/Mass Spectrometry
HASP	Health and Safety Plan
HSA	Hollow Stem Auger
IDW	Industrial Derived Waste
ITRC	Interstate Technical Regulatory Council
LTM	Long-Term Monitoring
MNA	Monitored Natural Attenuation
MS	Matrix Spikes
MSD	Matrix Spike Duplicates
MTBE	Methyl Tertiary Butyl Ether
NAPL	Non-Aqueous Phase Liquid
NBVC	Naval Base Ventura County
NETTS	National Environmental Technology Test Site
NAVFAC ESC	Naval Facilities Engineering Service Center
NRCS	Natural Resources Conservation Service
NTU	Nephelometric Turbidity Unit
ORP	Oxidation/Reduction Potential
OU	Operational Unit
PCE	Tetrachloroethylene
PVC	Polyvinyl Chloride
QAPP	Quality Assurance Project Plan
QC	Quality Control
RF	Response Factor
RI	Remedial Investigation
RITS	Remediation Innovative Technology Seminar

RSD	Relative Standard Deviation
TAC	Technical Advisory Committee
TAFB	Tyndall Air Force Base
TCE	Trichloroethylene
TIO	Technology Innovation Office
TRPH	Total Recoverable Petroleum Hydrocarbons
USEPA	United States Environmental Protection Agency
UST	Underground Storage Tank
VOA	Volatile Organic Analyte
VOC	Volatile Organic Compound
WDS	Well Design Specification

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the members of the ESTCP review committees, and current and past team members from the Army, Navy, and Air Force. In particular, we would like to thank Dale Lorenzana of General Dynamics, as his field and data management efforts proved critical to the success of this project. We would also like to acknowledge the efforts provided by Applied Research Associates, GeoInsight, GeoProbe, and other intergovernmental, academic, and private sector participants serving on our Technical Advisory Committee. Furthermore, key regulators from several states, as well as regulators serving on the ITRC Site Characterization and Monitoring Team, have been instrumental in helping achieve national acceptance for the cost-effective technologies demonstrated under the aegis of this ESTCP project.

EXECUTIVE SUMMARY

This report was completed as partial fulfillment of the obligations established for ESTCP demonstration project CU-0011. To date, regulatory approval of the use of direct-push (DP) well installations for long-term groundwater contaminant monitoring has been limited because a comprehensive performance analysis had not been performed. In response to this need, a multi-year demonstration effort was conducted under various site conditions to determine the representativeness of groundwater data collected from DP well installations relative to conventional drilled hollow stem auger (HSA) well installations. Chemical data resulting from sample collection and analyses was used to compare DP to HSA well performance on a long-term basis. In addition, hydrogeologic tests were conducted on a subset of the project well clusters to determine whether DP wells yield high quality hydraulic conductivity data relative to conventional HSA wells. The following conclusions serve as a summary to the key findings associated with this effort.

Final Conclusions from Statistical Analyses of Organic Contaminant Data:

- For most of the analytes and test sites, there does not appear to be a systematic bias that can be associated with DP well construction, including no-pack DP wells and DP wells of different diameters.

- For the few analytes where statistically significant differences were found between the pre-pack DP wells and the HSA wells, the differences were not large in magnitude and would not have impacted any management decision.

- The percent agreement between the no-pack DP wells and the HSA wells was essentially the same as that observed for the pre-pack DP wells.

- For several analytes at Tyndall AFB, large differences were observed between the mean concentrations for the no-pack DP wells and the HSA wells. Historical observations suggest that non-aqueous phase liquid (NAPL) may contribute to spatial variabilities.

- Higher-level analysis of variance (ANOVA) tests conducted on the Port Hueneme methyl tertiary butyl ether (MTBE) data revealed that any systematic differences associated with well design were small relative to the temporal variations and were not statistically significant. Temporal variations associated with DP wells agreed with those observed in the conventional wells.

- Correlation analyses conducted on the Port Hueneme MTBE data revealed that there were statistically significant correlations between the concentrations in the DP wells and those in the conventional HSA wells for all four of the DP well types at this site (including no-pack DP wells).

- Because much of the volatile organic compound (VOC) data from Dover AFB and Tyndall AFB was either near, at, or below the detection limit, statistical analyses (Pearson's Chi-square tests) were conducted to determine if there was agreement between detect vs. non-detect data for each of the DP well types. These analyses revealed that even at low analyte concentrations, there was no significant difference between the performance of any of the DP well types and the HSA wells at either site.

- There also were no statistically significant differences observed between VOC concentrations in the replicate HSA wells and the original HSA wells or between the replicate and original DP wells. In fact, spatial variabilities are demonstrated by the observation that for some sampling events, all the experimental well concentrations fall within the range of concentrations between the control drilled well and duplicate well.

Final Conclusions from Statistical Analyses of Inorganic Analyte Data:

- For most of the analytes and test sites, there does not appear to be a systematic bias that can be associated with DP well construction.

- The percent agreement between concentrations of inorganic analytes in samples collected from pre-pack DP wells relative to those in samples from conventional HSA wells appears to be slightly better than that achieved with the no-pack DP wells.

- In the few instances where statistically significant differences were found, the differences generally were not large in magnitude and most likely would not have impacted any management decision.

- Generally there were not any statistically significant differences between inorganic analyte concentrations in the replicate and original HSA wells. The one exception was at Dover AFB for Mn concentrations where differences were attributed to spatial heterogeneity at the site.

- Based upon the data from Phase II, leaching of metal constituents from the stainless steel components of the pre-pack DP filter packs was not a concern during this study.

Final Conclusions from Statistical Analyses of Purge Parameter Data:

- Statistical correlations were stronger (fewer statistical differences) for the purge parameters than for the VOCs and inorganic analytes. This was especially true for the pre-pack DP wells.
- The percent agreement between the pre-pack DP wells and the HSA wells and between the no-pack DP wells and the HSA wells was essentially the same.
- Purge parameters having the least agreement between the DP and HSA wells included turbidity and Dissolved Oxygen (DO).

- For those sites where there were statistically significant differences between the DP and conventional wells for turbidity, there was no consistent bias that could be associated with DP well construction, including well diameter or the presence or absence of pre-pack filters.
- For those sites where there was a significant difference between the DO content in the samples collected from the DP wells relative to the conventional well samples, there was no consistent bias that could be associated with the presence or absence of a pre-pack filter.

Final Conclusions from Statistical Analysis of Hydrogeologic Tests:

- Short duration pneumatic slug tests were determined to be a viable approach for determining hydraulic conductivity values in a high permeable formation. The results of a statistical comparison between the pneumatic slug tests lasting only a few seconds and the steady state pumping tests yielded no statistical difference.

- Hydraulic conductivity values in DP wells were found to be independent of pre-pack design, well radius, induced head, and test method (assuming the same screened interval).

- The hydraulic conductivity values determined from the different well types in the Port Hueneme B1 and B2 clusters had a mean post development value of 2 by 10^{-2} cm/sec and a standard deviation of 8 by 10^{-3}. The ANOVA analysis indicated there was no statistical difference amongst the pre-pack wells. Furthermore, there was no statistical difference between the pushed no-pack wells and the drilled wells. However, the ANOVA analysis indicated that there was a statistical difference between the latter wells and the pre-pack wells. The variance associated with hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells is largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method.

- Although development had an impact on the hydraulic conductivity for most of the wells, the impact was ambiguous. Of the 15 wells tested, 10 wells had statistical differences in hydraulic conductivity between pre- and post-development. Of the 10 wells, 5 wells showed increases in hydraulic conductivities and 5 wells showed decreases.

- Unsteady state, steady state pump tests, and pneumatic slug tests were shown to be statistically comparable means of determining hydraulic conductivity analysis in high permeable formations.

Key Conclusions:

- All sites included in our demonstration had both conventional drilled wells as well as direct-push wells. Our primary conclusion is that the chemical concentration results were

virtually identical given that the majority of the variability was due to spatial and temporal factors—not well type—and therefore we generally advocate the use of commingled data from both conventional and direct-push wells as appropriate for LTM applications.

- For the majority of the comparisons conducted during this demonstration project, management decisions would not be impacted regardless of whether the well is installed by drilled or DP methods.
- DP wells perform comparably to drilled wells with respect to organic solute concentration measurements, inorganic concentration measurements, and hydraulic assessment capabilities.
- For long-term monitoring (LTM) applications, DP wells are capable of providing representative chemical and hydraulic information.
- Adoption and regulatory approval of DP wells could lead to millions of dollars in savings for government and private entities.

As a result of this effort, two American Society for Testing and Materials (ASTM) standards and an Interstate Technical Regulatory Council (ITRC) Technical Regulatory Guide have been completed and released for government and industry use. In addition, regulatory approval and issuance of waivers have become more commonplace. Through on-going technology transfer vehicles such as ITRC workshops, Remediation Innovative Technology Seminars (RITS), and conference presentations, the results of this effort will be disseminated to regulators and users, ultimately leading to expedited and cost-effective well installation practices throughout the nation.

TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Objectives of the Demonstration	4
1.3 Regulatory Drivers	6
1.4 Stakeholder/End-User Issues	7
2.0 TECHNOLOGY DESCRIPTION	9
2.1 Technology Development and Application	9
2.2 Previous Testing of the Technology	13
2.3 Factors Affecting Cost and Performance	14
2.4 Advantages and Limitations of the Technology	19
3.0 DEMONSTRATION DESIGN	21
3.1 Performance Objectives	21
3.2 Selecting Test Site(s)	24
3.3 Test Site Description	24
3.4 Pre-Demonstration Testing and Analysis	36
3.5 Testing and Evaluation Plan	37
3.6 Selection of Analytical/Testing Methods	71
3.7 Selection of Analytical/Testing Laboratory	71
4.0 PERFORMANCE ASSESSMENT	73
4.1 Performance Criteria	73
4.2 Performance Confirmation Methods	74
4.3 Data Analysis, Interpretation and Evaluation	75
5.0 COST ASSESSMENT	135
5.1 Cost Reporting	135
5.2 Cost Analysis	138
5.3 Cost Comparison	142
6.0 IMPLEMENTATION ISSUES	143
6.1 Environmental Checklist	143
6.2 Other Regulatory Issues	143
6.3 End-User Issues	145
7.0 REFERENCES	149
8.0 POINTS OF CONTACT	153

TABLE OF CONTENTS (continued)

FIGURES

Page

Figure 2-1. Typical hollow-stem auger used to install conventional drilled wells for environmental monitoring purposes 10
Figure 2-2. Installation of an Exposed Screen DP Well Type 11
Figure 2-3. Pre-pack Well Screen 12
Figure 2-4. Installation of a Pre-Packed, Protected Screen DP Well Type 12
Figure 2-5. Illustration of a Completed Well Installation 13
Figure 2-6. Percentage DoD Savings for DP Well Installations Based on Well Diameter and Depth 16
Figure 2-7. Anticipated DoD Annual Savings by DP Well Installations for LTM 17
Figure 3-1. Dover National Test Site Well Clusters and Pairs 28
Figure 3-2 Former South Tank Farm 29
Figure 3-3. MTBE Plume intersecting Dover National Test Site 30
Figure 3-4. Locations of NAVFAC ESC Well Comparison Test Cells A and B as of May 1999 31
Figure 3-5. Hanscom AFB and Hanscom Field test site locations 32
Figure 3-6. Tyndall AFB Study Areas 34
Figure 3-7. CRREL Well Location Map, Phase II 38
Figure 3-8. Typical DNTS DP Well Construction Details 41
Figure 3-9. Soil classification logs, boring logs, grain size distribution and average permeability values for Evaluation Cell B 44
Figure 3-10. Well Cluster Representations for Cell B, Phase I 45
Figure 3-11. Cell B Layout, Phase I 46
Figure 3-12. Cell B Layout, Phase II 49
Figure 3-13. Map of Sites 1 & 2 showing the locations of the original Hanscom HSA monitoring wells 52
Figure 3-14. Map of Hanscom Site 21 showing the locations of the original HSA monitoring wells 53
Figure 4-1. Box and Whisker plots showing MTBE concentrations for each Port Hueneme sampling event 102
Figure 4-2. Box and Whisker plot showing MTBE concentrations in the four Hueneme well clusters 103
Figure 4-3. Box and Whisker plot showing MTBE concentrations for the five Hueneme well types 104
Figure 4-4. Comparison of Hueneme ¾” No-Pack DP Wells and 2” Control Wells 105
Figure 4-5. Comparison of Hueneme ¾” ASTM DP Wells and 2” Control Wells 106
Figure 4-6. Comparison of Hueneme ¾” Conventional DP Design and 2” Control Wells 107
Figure 4-7. Comparison of Hueneme 2” DP ASTM Wells and 2” Control Wells 108
Figure 4-8. MTBE Concentrations for Port Hueneme Cluster B1, September 2003 109
Figure 4-9. MTBE Concentrations for Port Hueneme Cluster B4, September 2003 109
Figure 4-10. Spatial Variability of Solute Caused by NAPL 125

TABLE OF CONTENTS (continued)

	Page
Figure 5-1. Percentage Savings for DP Well Installations Based on Well Diameter and Depth	139
Figure 5-2. Anticipated DoD Annual Savings by DP Well Installations for LTM	140

TABLES

Table 2-1. Cost Comparison Between DP and Drilled Monitoring Well Installations	15
Table 2-2. Advantages and Limitations of DP Wells	20
Table 3-1. Performance Objectives	21
Table 3-2. General Test Site Characteristics	24
Table 3-3. Summary of CRREL well construction information	39
Table 3-4. CRREL Accelerated Installation Well Construction Details	40
Table 3-5. DNTS Well Construction Details	42
Table 3-6. NAVFAC ESC Well Construction Details, Phase I	47
Table 3-7. Summary of well construction for conventional wells at the Hanscom sites	50
Table 3-8. Summary of well construction for Hanscom DP wells	51
Table 3-9. Tyndall Well Construction Details	54
Table 3-10. Project Milestones	56
Table 3-11. Volatile Organic Analyte List	61
Table 3-12. List of Laboratory Methods	62
Table 4-1. Performance Criteria Description, Primary or Secondary	73
Table 4-2. Expected Performance and Performance Confirmation Methods	74
Table 4-3. Mean values for field parameters at CRREL	78
Table 4-4. Results of statistical analyses of CRREL field parameter data	78
Table 4-5. Mean Specific conductance for CRREL well clusters	79
Table 4-6. Mean concentrations of detectable metals in CRREL wells	79
Table 4-7. Summary of statistical analyses of the CRREL inorganic and organic data	80
Table 4-8. Mean concentrations of TCE in CRREL wells	81
Table 4-9. Mean values for DNTS field parameters	81
Table 4-10. Summary of statistical analyses of 2-well data for field parameters at DNTS	82
Table 4-11. Mean values for Specific Conductance for DNTS well clusters	83
Table 4-12. Mean concentrations of field parameters for 5-well comparisons at DNTS	83
Table 4-13. Summary of statistical analyses of 5-well data for field parameters at DNTS	84
Table 4-14. Mean concentration of inorganics in DNTS wells	85
Table 4-15. Summary of statistical analyses of 2-well data for DNTS inorganic data	86
Table 4-16. Mean concentrations (µg/L) for 5-well comparison for DNTS inorganic analytes	87
Table 4-17. Summary of statistical analyses of 5-well data for inorganics at DNTS	88

TABLE OF CONTENTS (continued)

Page

Table 4-18. Mean and median organic concentrations in the wells at DNTS 89
Table 4-19. Summary of statistical analyses for 2-well data for organics at DNTS 89
Table 4-20. Mean concentrations of *cis*-1,2-dichloroethylene (μg/L) at DNTS 90
Table 4-21. Summary of statistical analyses of 5-well data for organics at DNTS 90
Table 4-22. Summary of results of Pearson's Chi-square test of detect/non detect matches for organic contaminants at DNTS 91
Table 4-23. Mean values for field parameters for Cells A and B, Phases 1 and 2 at NAVFAC ESC 93
Table 4-24. Summary of statistical analyses of field parameter data for 3-well comparisons at NAVFAC ESC 94
Table 4-25. Mean values for field parameters for Cell B, Phases 1 and 2 at NAVFAC ESC. 95
Table 4-26. Summary of statistical analyses of field parameter data for site B, 5-well comparisons at NAVFAC ESC 95
Table 4-27. Mean concentrations of inorganic analytes in the three ASTM designed wells at NAVFAC ESC 96
Table 4-28. Summary of statistical analyses of inorganic data from ASTM-designed wells (3-well data) at NAVFAC ESC 96
Table 4-29. Mean concentrations of inorganic analytes in 5 well types at NAVFAC ESC 97
Table 4-30. Summary of statistical analyses of inorganic data for site B comparing 5 well types at NAVFAC ESC 98
Table 4-31. Summary of statistical analyses of metals collected from all 7 wells at NAVFAC ESC 99
Table 4-32. Mean concentrations of MTBE in wells at Port Hueneme 99
Table 4-33. Summary of statistical analyses of MTBE data for NAVFAC ESC 100
Table 4-34. Partitioning of sum of squares for ANOVA model for NAVFAC ESC MTBE data 101
Table 4-35. Analysis of pairwise differences between DP wells and HSA wells for NAVFAC ESC MTBE data 104
Table 4-36. Mean values for purge parameters in Hanscom wells 111
Table 4-37. Results of statistical analyses of purge parameter data at Hanscom AFB 111
Table 4-38. Dissolved oxygen concentrations in Hanscom wells 112
Table 4-39. Mean concentration of inorganic analytes in Hanscom wells 113
Table 4-40. Summary of Statistical Analyses of Hanscom Inorganic Data 114
Table 4-41. Mean concentrations (μg/L) of organic contaminants in samples collected at Hanscom AFB 114
Table 4-42. Summary of statistical analyses of organic data for Hanscom AFB 115
Table 4-43. Mean values for field parameters measured at Tyndall AFB 116
Table 4-44. Summary of statistical analyses for Tyndall AFB field parameter data comparing four well types 117
Table 4-45. Mean values of the purge parameters for the six well types at Tyndall AFB ... 117
Table 4-46. Summary of statistical analyses for purge parameter data comparing six well types at Tyndall AFB 118
Table 4-47. Mean concentration of inorganic analytes in Tyndall AFB wells 118

TABLE OF CONTENTS (continued)

Page

Table 4-48. Results of statistical analyses of inorganic data at Tyndall AFB 119
Table 4-49. Mean concentrations in newly installed wells and older wells at Tyndall AFB 120
Table 4-50. Mean concentrations in the wells at Tyndall AFB 120
Table 4-51. Summary of statistical analyses of organic contaminants at Tyndall AFB 121
Table 4-52. Mean concentrations of organic analytes by for each well cluster (with three or more sampling events) at Tyndall AFB 122
Table 4-53. Summary of the statistical analyses of six well types (including replicate wells) at Tyndall AFB 126
Table 4-54. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA control wells vs. 1.5-inch no-pack DP wells at Tyndall AFB ... 126
Table 4-55. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA wells vs. 1-inch pre-pack DP wells at Tyndall AFB 127
Table 4-56. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA control wells vs. 0.5-inch pre-pack DP test wells at Tyndall AFB 128
Table 4-57. Summary of statistical analyses comparing pre-pack DP and HSA wells 129
Table 4-58. Summary of statistical analyses comparing no-pack DP wells and HSA wells .. 129
Table 5-1. Cost Tracking 136
Table 5-2. Itemized Cost Assumptions 137
Table 5-3. Life Cycle Cost Comparison Between DP and Drilled Monitoring Wells 137
Table 5-4. Cost Comparison Between DP and Drilled Monitoring Well Installations 139
Table 5-5. Life Cycle Cost Comparison Between DP and Drilled Monitoring Wells 141

APPENDICES

Appendix A: Quality Assurance Project Plan (QAPP) A-1
Appendix B: Hydraulic Conductivity Comparison B-1
Appendix C: Phase II Work Plan C-1

1.0 INTRODUCTION

1.1 Background

During environmental site characterization, remediation, and compliance efforts, groundwater monitoring wells have served as the conventional tool-of-choice for accessing groundwater samples. A typical sequence of events in the life cycle of a contaminated site would include the discovery of a release, an initial source removal response, initial site characterization efforts, generation of a conceptual model, detailed site characterization efforts, remedial design, remedial system installation efforts, system performance monitoring, compliance monitoring and site closure. Monitoring wells are generally installed at key steps in this sequence of events to define the extent of the contaminant plume, determine where and how fast it is migrating, select an optimal remediation method, evaluate the effectiveness of a remedial option, and to serve as long-term sample and data access conduits for compliance purposes. In most cases, critical decisions are based on data collected from wells that are installed using a drilling technique such as hollow stem auger (HSA).

Recent increases in the application of direct-push (DP) technologies during site characterization have led to rapid site characterization efforts and development of more detailed conceptual and hydrogeologic models. The Cone Penetrometer Test (CPT) (ASTM D6067) is an excellent tool for mapping stratigraphy and locating target layers for sampling. Additional sensors such as electrical conductivity, piezocone, and optical contaminant detectors have been integrated into direct-push systems. Furthermore, direct-push soil (ASTM D6282) and water sampling (ASTM D6001) can be used in lieu of drilling to rapidly determine contaminant distributions and identify strata of concern.

Recently developed DP technologies provide the means for collecting faster, less expensive groundwater samples when compared to conventionally drilled wells. In addition, when compared to conventional applications, worker exposure to contaminants is significantly lower when installing DP wells and deploying sensor probes. The most extensive use of these cost-effective technologies has been for initial site characterization. DP wells, initially used almost exclusively as temporary installations for characterization purposes, have not been widely accepted for long-term monitoring (LTM) of contaminant and hydrogeologic properties at remedial action sites. For broad acceptance of DP well LTM applications, comparisons between conventionally drilled wells and DP wells needed to be conducted to validate these innovative approaches. If comparable and representative DP well performance could be demonstrated, widespread regulatory acceptance of these cost-effective methods should be forthcoming.

Since groundwater monitoring wells are a major element of nearly all contaminated site characterization, remediation, compliance, and post-closure monitoring efforts, regulatory acceptance of DP wells can have a pronounced impact on overall cleanup costs throughout the Department of Defense (DoD) complex. The magnitude of the potential savings is significant considering that the DoD is steward of nearly 25 million acres of land in the United States alone (U.S. DoD, 1995). Since the early 1980's DoD has acknowledged that nearly 30,000 contaminated sites exist in the United States; about half of which have not been cleaned up as of 2000 (USEPA, 2000). Even if monitoring wells are installed at only 10,000 of the DoD sites awaiting cleanup, savings of just $100 per well can quickly add up to millions of dollars saved

overall. Savings in the tens of millions of dollars are more likely given the extent of cleanup estimates and the fact that monitoring wells will be potentially used at every site. The EPA recently estimated that over 350,000 hazardous waste sites would require restoration over the next 30 years at a cost of over $250 billion, with the DoD accounting for approximately 6,400 sites (U.S. EPA, 2004).

The main regulatory concerns regarding the use of direct-push wells for long-term groundwater monitoring include the following:

1. Filter pack materials are either not used or are not based on grain size distribution of the formation in contact with the well screen section;
2. Minimum annular sealing requirements based on drilled well specifications exist for most states, yet DP wells have much smaller annular spaces than conventional drilled wells;
3. Annular sealing may not be complete for pre-packaged well screen devices and tremmied filter pack applications under certain geologic conditions; and
4. Until recently, chemical and hydrogeologic performance comparisons between DP wells and conventional drilled wells had not been demonstrated.

Pre-packaged well screen materials have recently become available for direct-push applications. This recent development is significant in that it allows for filter pack design based on grain size distribution of the screened formation in accordance with the American Society for Testing and Materials (ASTM) Standard Practice for Design and Installation of Groundwater Monitoring Wells in Aquifers (ASTM D5092). This development offers an alternative to highly uncertain tremmie filter pack installation methods. Under certain conditions, there is no guarantee that annular sealing is complete for direct-push wells. However, recently developed annular sealing devices such as bentonite sleeves can reduce the chance for vertical cross-contamination within porous aquifer media. Vertical cross contamination is a concern for coarse, unconsolidated, water-saturated sandy materials that can be mobilized during well development. However, these types of regimes tend to be more amenable to successful development than fine grained strata, as the mobile particles can more readily fill-in open spaces resulting from the difference in diameter between the push tool and the pre-pack filter device. For finer strata, the open space may remain. However, when fine and coarse grain strata are encountered in the impacted soils, it is recommended that setting well screen and filter pack into the fine strata be generally avoided, as contaminant migration through these zones can be impeded, thereby rendering the data questionable. Furthermore, clogging of the filter pack set into fine-grained strata can lead to well failure. These considerations apply equally to conventional wells as well as DP wells.
As an example of the challenges posed prior to the initiation of this project, the State of California Department of Water Resources (1981) requires the following:

> "An oversized hole, at least 4 inches (100 millimeters) greater than the diameter of the conductor casing, shall be drilled to the depth specified … and the annular space … filled with sealing material."

The purpose of the 2-inch (5.08-cm) increase in annular sealing radius is to ensure that formation particles are inhibited from entering the well by enabling installers to effectively set a filter pack using a tremmie technique to fill the annular space (typically using a funnel, which is sometimes

connected to a hose, that fits in the annular space). However, since the design theory of sand pack gradation is based on mechanical retention of the formation particles, a pack thickness of only two or three grain diameters is required to retain and control the formation materials (Driscoll, 1986). Since it is impractical to tremmie a filter pack into a drilled well annulus only a fraction of an inch thick and expect the material to completely surround the well screen, the 2-inch (5.08-cm) requirement has been used as a minimum criteria to provide the installer a level of confidence based on the tooling available. Current designs for pre-packaged direct-push well screens allow for the use of “thin” filter packs, and preclude the use of tremmie techniques. Therefore, the 2-inch (5.08-cm) State of California requirement may not be necessary for direct-push pre-packed wells, as the tremmie technique is not employed.

On August 11, 1999, an advisory committee comprised of experts from industry, government regulatory entities, and academia was assembled in Port Hueneme, California to determine how best to compare the performance of direct-push and drilled monitoring wells. Of particular concern was the comparison of chemical data (e.g., concentration of contaminant of concern and monitored natural attenuation indicator parameters) and hydrogeologic data (potentiometric surface measurement and hydraulic conductivity assessment) for the different types of wells. Detailed discussions related to direct-push well construction, experimental design, well configuration plans, statistical analysis, and sampling approaches were considered during the generation of the project work plan.

This project was conducted in two phases. Phase I, spanning from 1999 to 2001, consisted of side by side comparisons of samples collected from conventional drilled wells and DP wells, and analyzed for specific organic and inorganic solute concentrations evaluated at sites located at Hanscom AFB, Tyndall AFB, Dover AFB, and NBVC Port Hueneme. Following initial data assessment activities and promising results, a second advisory committee workshop was held in December of 2001 in Port Hueneme, California to determine the steps required to obtain regulatory approval on a national level. The committee determined that a follow-on Phase II effort would be required, with the following primary goals:

- identify shortcomings in the Phase I efforts;
- consult with regulatory representatives and leading industry experts to articulate specific experimental design constraints required to achieve regulatory acceptance for DP well installation methods;
- generate a revised Work Plan;
- implement the revised Work Plan;
- facilitate DP well technology transfer; and
- complete the technology certification process.

Details regarding specific Phase II recommendations are presented in Sections 1.2, 3.5 and Appendix C. In response to these recommendations, Phase II efforts were conducted at sites located at Tyndall AFB, Dover AFB, and NBVC Port Hueneme. Hanscom AFB was no longer monitored as part of Phase II, while a site at the U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (Army CRREL) was incorporated into the demonstration. While preliminary field work occurred at Army CRREL during Phase I, sampling from some of the deeper DP wells was not successful using commercially available technologies until Phase II

had been initiated. Furthermore, Cell A from NBVC Port Hueneme was no longer to be part of the Phase II effort. Additional details regarding site-specific well configurations and well designs are discussed below and in Section 3.5.

During Phase I, California EPA Certification for DP wells was initially pursued. In fact, CalCert Program Directors were involved in the initial experimental design for the Port Hueneme site comparison, as well as the December 2001 Advisory Committee workshop for this multi-site project. However, due to budgetary constraints, the CalCert group was no longer supported by the State of California. At approximately the same time, the Interstate Technology Regulatory Council (ITRC) was created, offering a technology transfer vehicle that can reach regulators at multiple states simultaneously (as opposed to obtaining California certification, then seeking reciprocity through interstate and federal lobbying). The project group collectively decided to pursue national acceptance for DP well use for LTM applications through development of an ITRC Technical Regulatory Guide.

Additional details and results from Phase I and Phase II efforts are provided in the following sections.

1.2 Objectives of the Demonstration

The purpose of this project was to rigorously compare the results of laboratory analyses conducted on samples obtained from DP wells to those obtained from wells installed utilizing conventional techniques (e.g., HSA wells). Hydraulic comparisons comprised of pneumatic slug and conventional aquifer tests were also performed in selected wells. Ultimately, the goal of this demonstration is to determine whether DP wells can yield representative data for LTM applications. Provided this is the case, the results will be used to convince regulators that DP wells should be accepted and their use encouraged throughout the industry.

A primary benefit of validating direct-push technology and promoting its acceptance and use for groundwater sampling and hydraulic assessment is the reduction of well installation and LTM costs at contaminated sites. Furthermore, reduction of worker exposure is also a significant benefit associated with the implementation of these cost-effective monitoring options.

Although DP-installed monitoring points have been accepted by the regulatory community for characterization of a groundwater contamination plume, there was, until recently, little data to support their use for long-term regulatory monitoring. This project included rigorous sampling efforts to establish a database of water quality and chemical analytical results comparing samples collected from both well types over a 15-month period for Phase I and over 24 months for Phase II, for a total of 13 sampling rounds. These data were analyzed using statistical tests of hypotheses to determine whether statistically significant difference existed in the measured groundwater quality parameters obtained from the two well types. Regulatory approved protocols for well installation and development, groundwater sampling, and field and laboratory analytical methods were specified and adhered to, ensuring the results of the experiment were valid in a regulatory context.

Five field sites were included in the study to represent a variety of geologic conditions as well as a cross-section of regulatory domains (e.g., EPA regions and states) and contaminant types. DP

wells were installed adjacent to, and paired with, existing auger-drilled wells at the following facilities: Army CRREL in Hanover, NH (EPA Region 1); Dover National Test Site (DNTS) at Dover AFB, DE (EPA Region 3); the Naval Facilities Engineering Service Center (NAVFAC ESC) at Port Hueneme, CA (EPA Region 9); Tyndall AFB, FL (EPA Region 4); and Hanscom AFB in MA (EPA Region 1).

For Phase I, five sampling rounds were conducted over a 15-month period at each of the sites. Groundwater samples were collected and the parameters examined under long-term site compliance monitoring were evaluated (e.g., chemical concentrations, oxidation-reduction potential [ORP], pH, temperature, conductivity, turbidity, and dissolved oxygen [DO]). The target analytes for this project included: tetrachloroethene (PCE), trichloroethene (TCE), cis-1,2-dichloroethene (cis-DCE), trans-1,2-dichloroethene (trans-DCE), vinyl chloride (VC), benzene, toluene, ethylbenzene, o,m-xylene, p-xylene, 1,4- dichlorobenzene (DCB), trichloroethane (TCA) and methyl tertiary butyl ether (MTBE). Existing conventional wells were used at all sites except Port Hueneme, where NAVFAC ESC installed new conventional and DP wells in customized configurations for a precursor to this study. New DP wells were installed at all sites except Hanscom AFB, since DP wells were installed in 1996 for a previous study. Plans detailing the specific well construction details at each site are provided in Section 3.5.

While most of the Phase I objectives were met, the power of the statistical tests (or likelihood that one will identify a significant difference when one exists) was reasonable for some of the comparisons, and low for others, implying that conclusions regarding well performance were not yet adequately strong. Perhaps even more importantly, regulators and industry practitioners need to be confident that DP wells provide reliable data for long-term groundwater monitoring applications spanning several successive seasonal events. Therefore, collection of additional sampling rounds from each well in the study was implemented as part of Phase II. Furthermore, there remained a need to compare HSA wells to other nearby identically designed HSA wells to better understand the variability within the solute concentration distribution and to further support claims that well type differences impart less variability than spatial heterogeneity, even at extremely close proximities (e.g., within one meter). Therefore, as part of Phase II, new HSA wells were installed in selected clusters, and comparison of the HSA to HSA variability with that observed between the HSA and direct-push designs was implemented. Selected Dover and Port Hueneme clusters also were augmented with duplicate direct-push designs.

Efforts at CRREL to recover samples from the deep (approximately 125 feet below ground surface (bgs)) wells proved challenging during Phase I. Phase II efforts therefore included installation of a slightly larger diameter direct-push design to facilitate the use of pumps capable of yielding representative samples at flow rates and depths of interest.
To attain outside review of the well comparison study interim data and facilitate regulatory acceptance, the project team members (Bill Major, Louise Parker, Dr. Mark Kram, and Dale Lorenzana) participated in the development of an ITRC Technical Regulatory Guidance document (ITRC, 2006), as well as an on-line workshop that covered key findings from this demonstration. Critical components from this demonstration project were used to generate a case study that proved pivotal to the regulatory acceptance of DP wells for LTM applications. Furthermore, these results were used by several key industry and regulatory entities at state and local levels throughout the nation to help justify the acceptance of variances granted to groups

seeking approval for the use of DP wells for site specific LTM applications (i.e., San Diego County, 2004).

1.3 Regulatory Drivers

Most states have regulatory guidelines and bulletins that were developed prior to the advent of DP wells. Therefore, these regulatory tools are based on conventional drilled well designs, which are not as cost-effective as DP designs, as they generate significantly more solid and liquid wastes and require additional installation time. The main regulatory concerns regarding the use of DP wells for long-term groundwater monitoring in place of conventionally drilled wells, and relevant discussions of how these concerns have been addressed, is listed below.

1. There is a need to demonstrate that there is no difference in groundwater chemistry and hydraulic measurements between HSA wells and DP wells for long-term (greater than one year) monitoring periods. These analytical results must be supported by appropriate statistical tests applied to groundwater sample data collected from comparably constructed DP and conventionally drilled wells. This demonstration addresses this need through incorporation of carefully controlled well design representatives, sample collection and analyses over several years of observation, evaluation at sites with different geologic and contaminant regimes, and appropriate statistical data treatment. While variability is anticipated, use of appropriate statistical approaches for comparison can help distinguish between variance attributed to spatial heterogeneity, temporal dynamics, and well type. This demonstration effort was designed to specifically address regulatory and technical concerns articulated by industry and regulatory experts.

2. State regulators generally have minimum annular space sealing requirements based on drilled well specifications. These specifications often preclude the use of small diameter DP wells for LTM, since annular spacing is limited by the diameter of the push tool. In the case of direct-contact DP wells (i.e., those whose outer surface is in intimate contact with the soil formation due to displacement during driving) there is no annular space.

   The State of California Department of Water Resources (1981) requires the following:

   > "An oversized hole, at least 4 inches (100 millimeters) greater than the diameter of the conductor casing, shall be drilled to the depth specified … and the annular space … filled with sealing material."

   The purpose of the 2-inch (5.08-cm) increase in annular sealing radius is to ensure that formation particles are inhibited from entering the well by enabling installers to effectively set a filter pack using a tremmie technique to fill the annular space (typically using a funnel, which is sometimes connected to a hose, that fits in the annular space). However, since the design theory of sand pack gradation is based on mechanical retention of the formation particles, a pack thickness of only two or three grain diameters is required to retain and control the formation materials (Driscoll, 1986). Since it is impractical to tremmie a filter pack into a drilled well annulus only a fraction of an inch thick and expect the material to completely surround the well screen, the 2-inch (5.08-cm) requirement has been used as a minimum criteria to provide the installer a level of confidence based on the tooling available.

Current designs for pre-packaged direct-push well screens allow for the use of "thin" filter packs. Therefore, the 2-inch (5.08-cm) requirement may not be necessary for direct-push pre-packed wells, as the tremmie technique is not employed.

3. It is often speculated that annular sealing may not be complete for pre-packaged well screen devices and tremmied filter pack applications under certain geologic conditions. For instance, in clay formations, push holes may not adequately collapse around the riser during well development. Recent developments in pre-pack filters, annular sealing devices, and robust development techniques reduces concerns attributed to this sealing issue. Furthermore, the current tendency towards short-screened wells will further reduce the risk of seal breach.

4. With DP wells, filter pack materials are either not used, or when used, are not typically based on grain size distribution of the formation in contact with the well screen section. An ASTM standard (D5092) exists for filter pack design in drilled wells. Similar to annular sealing requirements, some state regulations explicitly require a filter pack designed in accordance to the formal specifications outlined in D5092. There is therefore an institutional barrier to the use of direct-contact DP wells and non-pack DP wells, which do not typically employ a conventional filter pack. When this project was initiated, no ASTM standards existed for DP wells. However, project team members participated in the development of two new ASTM standards to help reduce these institutional barriers (ASTM D6724 and ASTM D6725). Furthermore, to address the filter pack design concerns, Kram and Farrar developed a well design software package to allow for selection of appropriate filter pack and screen slot based on CPT derived soil type characteristics (U.S. Patent Number 6,317,694). This approach is based on well design recommendations articulated in ASTM D5092. Current efforts to license this technology are underway.

5. Prior to this effort, data did not exist to support the use of DP wells in a broad range of geologic conditions, thus reinforcing a tendency to accept them only on a case-by-case basis through regulatory variance. This demonstration attempts to provide the necessary data to alleviate regulatory concerns about DP well applicability in a broad range of geologic conditions. To help meet the critical objective of convincing regulators that DP wells should be accepted and their use encouraged throughout the groundwater monitoring industry for LTM applications, project team members (Bill Major, Louise Parker, Dr. Mark Kram, and Dale Lorenzana) participated in the development of an ITRC Technical Regulatory Guidance document (ITRC, 2006), as well as an on-line workshop that covers key findings from this demonstration. Key components from this demonstration project were used to generate a case study that proved pivotal to the regulatory acceptance of DP wells for LTM applications. Furthermore, these results were used by several key industry and regulatory entities at state and local levels throughout the nation to help justify the acceptance of variances granted to groups seeking approval for the use of DP wells for site specific LTM applications (i.e., San Diego County, 2004).

1.4 Stakeholder/End-User Issues

Successful demonstration of DP wells accuracy for long-term chemical and hydraulic measurements will lead to significant cost savings on a government, national, and international level. However, prior to installation of DP wells, site managers must determine whether DP

technologies can be implemented at their site. Site-specific lithology will dictate whether DP technologies can be used at a specific site. Sites comprised of unconsolidated alluvial materials are candidates for DP technologies. However, sites comprised of consolidated materials, cobbles, very tight sands, caliche, anthropogenic refuse, and cemented materials in the shallow zones (i.e., less than 75 feet [22.86m] below ground surface) can prove challenging to DP applications. On-going efforts to increase the push capabilities through rotary drill integration, sonic techniques, and enforced hammer applications have recently increased the probe advancement and well installation capacity in challenging soils.
Another key consideration is depth of investigation. While DP wells have been installed with screens set to depths beyond 100 feet [30.48m] bgs, these are more commonly used at sites where depths of interest are less than 75 feet [22.86m] bgs. When advancing DP wells at dense non-aqueous phase liquid (DNAPL) sites, it is critical to identify potential vertical flow barriers such as clay lenses, and to appropriately seal these off through emplacement of expansive materials in the annular spacing (e.g., hydrated bentonite chips, pellets, and pre-pack bentonite sleeves).

Well design is also a critical factor. ASTM D5092 articulates appropriate filter pack and screen slot size recommendations based on screened formation grain size characteristics. Prior to implementation of this demonstration, regulators expressed concern that DP wells did not conform to ASTM D5092 recommendations. Most either did not have filter packs, or used a "one-size-fits-all" design that was not appropriate for all installation environments. For this demonstration, several well design applications were utilized. Representative designs included "one-size-fits-all," ASTM D5092 designs based on soil samples and grain size distributions, and no-pack representatives. When this project was initiated, no ASTM standards existed for DP wells. However, project team members participated in the development of two new ASTM standards to help reduce these institutional barriers (ASTM D6724 and ASTM D6725). Furthermore, to address the filter pack design concerns, Kram and Farrar developed a well design software package to allow for selection of appropriate filter pack and screen slot based on CPT derived soil type characteristics (U.S. Patent Number 6,317,694). This approach is based on well design recommendations articulated in ASTM D5092.

Perhaps most significantly, when planning for use of DP wells, a significant cost advantage can be realized when coupling monitoring well installation activities with site characterization activities associated with solute plume delineation. Since many direct-push monitoring well installation devices can be used to deploy direct-sensing probes, Triad-based expedited site characterization activities can be augmented with DP wells without an additional mobilization requirement. This approach significantly reduces the time and labor associated with report review, contracting, and permitting activities often required when plume delineation field efforts are limited to field screening and reporting activities. In addition, the plume delineation field screening data can be utilized to determine appropriate and optimal groundwater monitoring locations and site-specific designs while the investigators remain in the field.

2.0 TECHNOLOGY DESCRIPTION

2.1 Technology Development and Application

DP techniques have been used to obtain stratigraphic information and soil engineering properties for several decades. DP is sometimes used as an alternative to drilling for the screening phase of a site characterization program and for temporary monitoring of remediation systems. DP approaches to site characterization and monitoring offer significant advantages by providing detailed, continuous subsurface stratigraphic information in real time while producing little or no drilling waste, thereby limiting worker exposure to hazardous materials and resulting in more rapid and discrete characterization efforts. Due to the high cost of drilling at contaminant sites, both the DoD and the Department of Energy (DOE) implement aggressive programs to develop chemical sensors and sampling methods for minimally intrusive direct-push methods such as the Cone Penetration Test (CPT) (Gildea *et al.*, 1995; Montgomery *et al.*, 1996; Farrington and Bratton, 1997; Kram, 1998, 2004, 2006a, 2006b; Lieberman *et al.*, 1991, 1997, and 1998; McCall *et al.*, 2006).

DP wells can be installed using either a static force system or a dynamic system. Static force systems consist of hydraulic ram units with a static weight of 20 to 30 tons [18,144 to 27,216 kg], while dynamic systems consist of a percussion hammer and hydraulic rams mounted on a smaller truck or track unit. Since the mid to late 1990's, DP has been used for installation of small-diameter (i.e., 0.5 to 2.0 inch [1.27 to 5.08cm] diameter) monitoring wells. A DP-installed monitoring well consists of a polyvinyl chloride (PVC) screen and riser that are advanced into the soil behind a dedicated drive point. After the well is installed, the drive point remains in place and serves as the bottom cap.

Conventional HSA monitoring wells are installed by drilling a borehole while clearing the soil cuttings brought to the surface by the auger flights as depicted in Figure 2-1. The soil cuttings brought to the surface are continually placed in drums by the drillers, and site cleanliness is not easy to maintain. Workers are exposed to the cuttings at several stages within the process. In the case of conventionally drilled wells, the borehole is held open by the hollow stem auger flights used to drill the hole. The well casing is typically constructed of schedule 40 PVC, but may also be constructed of steel or stainless steel. Well casings are typically 2 or 4 inches [5.08 to 10.16cm] in diameter but may vary from 0.5 to 8 inches [1.27 to 20.32cm] or larger. The well casing is lowered down inside the hollow stem auger to the intended design depth and a sand backfill is placed around the screened section as the augers are carefully removed. This critical filter pack sand backfill is placed in position around the well screen using a tremmie approach, whereby sand is poured into a funnel connected to a hose lowered to the point of placement. The sand pack height is periodically checked using a plumb device. However, quality control is often questionable, and the pack is therefore often "bridged" leading to incomplete protection of the screened zone. A seal is typically installed above the screen section to prevent contaminant migration from geologic units above the screen down along the well casing. This seal, typically 2 to 4 feet [0.61 to 1.22m] in vertical thickness, is generally constructed of bentonite clay introduced as dry material that expands upon hydration. The remainder of the hole is back-filled with a cement grout and a concrete apron is installed at the surface to house the traffic box.

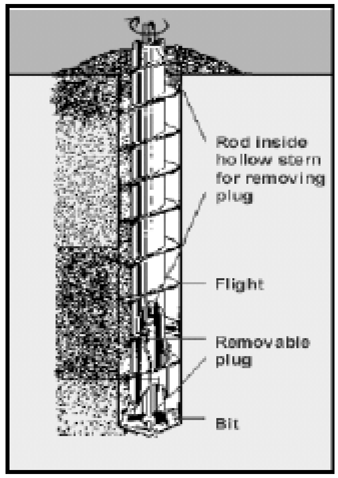


Figure 2-1. Typical hollow-stem auger used to install conventional drilled wells for environmental monitoring purposes.

The two main categories of DP well systems include exposed screen and protected screen representatives. Exposed screen wells are installed with the well screen in contact with the surrounding formation. These represent one form of “no-pack” wells, as they do not employ the use of a filter pack. When this project was first initiated, exposed screen no-pack wells were more commonplace. However, in recent years these options have become less popular. In protected screen configurations, the screens are enclosed in the push rods, which are retracted after reaching the target installation depth. With respect to filling in the annular space between the screen and the formation left by rod retraction, protected screen configurations can be used to incorporate either pre-packed filter systems, tremmied filter systems, or no filter system (i.e., another type of no-pack wells). ASTM D5092, D6001, D6724, and D6725 describe these concepts in greater detail.

For the exposed screen method, a CPT or other direct-push rig and rod string are utilized to install a direct-contact well, also classified as an exposed screen sampler (ASTM D6001), as shown in Figure 2-2. The well screen and riser pipe are advanced by the CPT rods, which are in compression, using the weight of the CPT truck as reaction mass. The options for exposed screen casing size are limited when compared to conventional drilled wells, since the well material has to fit closely around the push rods. Casing sizes are typically 1½ or 2-inch [3.81 to 5.08cm] inner diameter. Exposed screen wells do not have a filter pack because they do not provide an annular space between the well screen and surrounding formation. Also, since the outer well screen is exposed during driving, rigorous development is necessary following installation to remove sediments from the screen slots and to ensure the screened interval is free of any potential contamination acquired while passing though a shallower stratum.

The exposed screen system was selected as a DP well representative for several well pairs and clusters within this study, because it allows for a close match of well construction details (slot size, screen length, diameter, and material) relative to several of the conventionally drilled wells. For all the other wells, protected screen designs were installed. DP well screens were designed and installed to match the conventional well screen lengths and depths as closely as possible.

Well screen slots are designated by the width of the slot, with the most common options being 0.010 inch or 0.020 inch (10-slot or 20-slot, respectively). For this study, slot widths for the DP wells were designed to match the conventional well slot widths for several cluster and pair representatives. For some of the sites, alternative slots were selected for various reasons. For instance, at Port Hueneme, the HSA wells and at least one DP representative were designed using ASTM D5092 filter pack and slot size specifications. In addition, for several clusters, the most commonly used filter pack and slot size option (e.g., 20/40 sand pack with an 0.010 slot) was used to represent wells typically installed within the industry when ASTM D5092 is not properly adhered to. For some sites (e.g., sand and silty sand), using the “one-size-fits-all” 20/40 sand and 10-slot option may not be a problem. However, for finer formation materials, well failure can result if the proper design is not utilized. This is a critical factor that regulators recognized early on in their criticism of DP wells. This factor served as the main driver for Kram and Farrar to devise their well design specification approach that is based on CPT soil descriptors (U.S. Patent 6,317,694).

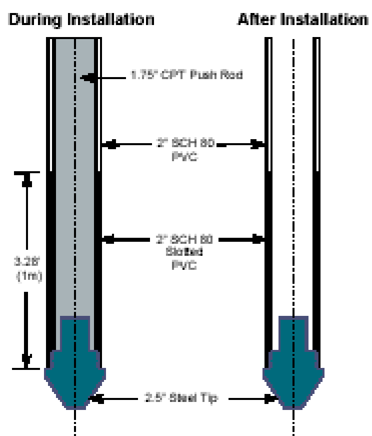


Figure 2-2. Installation of an Exposed Screen DP Well Type.

Several DP well installations included protected screen systems incorporating pre-packaged filter packs (Figure 2-3), or “pre-packs.” The internal well screen is typically comprised of Schedule 40 PVC with factory cut slots. The external filter media support is typically constructed with stainless-steel wire cloth with a pore size of approximately 0.011 inch [0.28mm]. Graded silica sand is used for the filter media. Specification of filter pack and casing screen slot criteria were based on grading curve results and ASTM D5092 recommendations. The technique for installing pre-packed protected screen systems is illustrated in Figure 2-4. A DP device is used to install and seal, in-place, the small diameter wells in one pass. These smaller wells are often installed using a Geoprobe, a conventional CPT, or similar machine that uses either a percussion hammer or hydraulic device to drive the well into the ground. The well installation system consists of an expendable drive point connected to a schedule 40 PVC riser pipe. An expandable annular seal can be threaded immediately above the screened section. As the drive casing is removed, the seal expands when exposed to water, effectively preventing grout intrusion into the screen interval. A seal is placed in the annulus between the borehole and the riser pipe on top of the expandable seal by use of a bentonite sleeve, tremmie method or by gravity feed. Sufficient time is allowed for bentonite hydration and expansion prior to grouting the remaining annulus.

The volume and elevation of the bentonite seal material is measured and recorded on the well completion diagram. Alternatively, non pre-packed wells can be installed with the protected screen approach, and the annular space filled by tremmie insertion of filter pack and seal material. This was more commonly practiced prior to the development of pre-pack options.

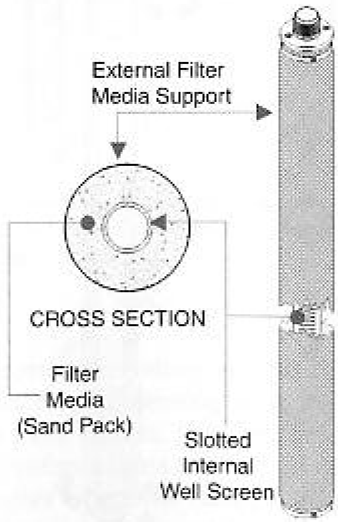


Figure 2-3. Pre-pack Well Screen (from McCall *et al.*, 2006).

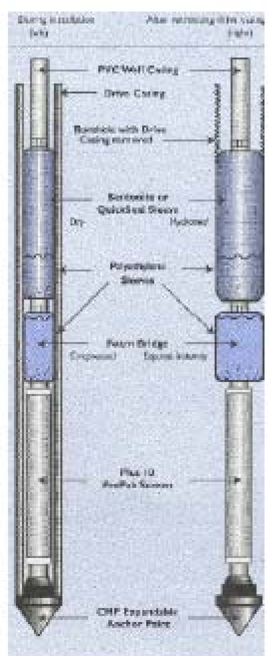


Figure 2-4. Installation of a Pre-Packed, Protected Screen DP Well Type.

For all well installations in this study, protective casings or access covers were installed to secure and protect the wells. At-grade access covers were set in concrete pads, which were sloped to promote water drainage away from the well. The top of the riser pipe was notched so that measured water levels maintained a constant vertical and horizontal reference. Labels were

affixed to the vault lids to mark the well location ID and locations and elevations surveyed. Figure 2-5 illustrates a typical well completion, including the surface seal.

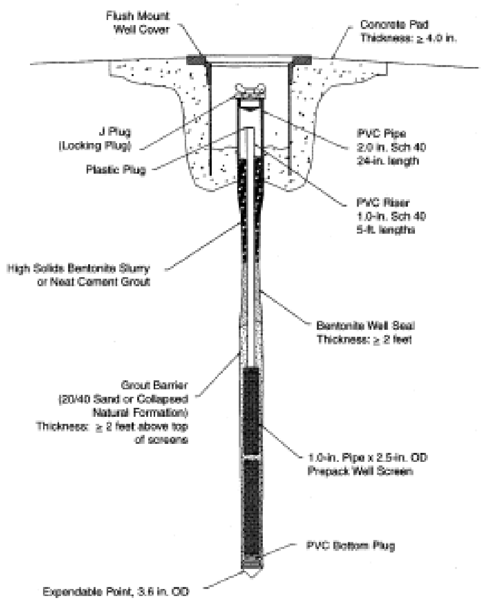


Figure 2-5. Illustration of a Completed Well Installation.

ASTM D5521 provides guidance on well development. The use of a surge block in combination with continuous groundwater withdrawal was used to develop several of the wells associated with this project, while the remaining wells were developed using a combination plunger block and pump approach.

2.2 Previous Testing of the Technology

Several previous investigations have been completed to evaluate the use of DP well installations when compared to conventional (auger-drilled) wells (McCall, *et al*. 1997; McCall, 1999; Kram *et al*., 2001; British Petroleum and USEPA, 2002). Prior to this effort, no study focused on long-term data quality comparisons.

Beginning late in 1995, Applied Research Associates, Inc., under contract with the Air Force Research Laboratory (AFRL) began a program to compare the performance of direct-push and conventional monitoring wells for long-term groundwater monitoring of corrective action sites. Sites at Hanscom Air Force Base (AFB) and Hanscom Field in Massachusetts were selected for this initial study. A comprehensive Work Plan was prepared that included protocols for well installation, sampling, chemical analysis, and statistical comparisons, as well as a site specific Health and Safety Plan (HASP) and Quality Assurance Project Plan (QAPP). DP wells were successfully installed adjacent to 43 existing conventional monitoring wells, creating matched well pairs installed to depths ranging from 13 to 65 feet [3.96 to 19.81m]. Screen lengths, elevations of screened intervals, and well diameters were matched as closely as possible in all pairs. Two rounds of sampling and analysis were completed, adhering strictly to a low-stress (low-flow) sampling protocol and evaluation of a suite of ten volatile organic analytes using EPA

SW-846 methods. Paired data statistical tests were used to compare the performance of the two well types because of their ability to neutralize the influence of extraneous factors (e.g., location of the well pair within the contaminant plume, location with regard to local variation in the hydrogeology, length and depth of the screened interval, etc.) which could vary from pair to pair but were assumed to have the same influence within each pair.

Statistical testing was conducted on nine analytes and five water quality parameters that were measured during purging of the wells for sample collection. The parametric Student's *t*-Test and non-parametric and Wilcoxon Signed Rank Test were applied to the data set, as appropriate, to test the null hypothesis that the mean of differences between paired observations was equal to zero.

With only one exception among all analytes and water quality parameters for which results were compared, the results showed no statistically significant difference between the performance of the two well types. However, due to ongoing remediation efforts at the sites, the data generated during the study produced a large number of non-detects, which complicated the statistical analyses and decreased the number of observations in the statistical samples, thus limiting the power of the tests.

The USEPA Technology Innovation Office (TIO) (Crumbly, 2000) conducted an independent review of the data. They concluded that the limited data set warranted additional sampling in more diverse geological settings. Thus, the current study expanded both the number of sampling events as well as the number and geologic diversity of sites involved.

Kram *et al.*, (2001) conducted a number of detailed statistical analyses of water samples collected from clusters of co-located direct-push installed wells and conventional drilled wells. For each of the clusters, screens of equivalent lengths were installed at the same depths within the leading edge of the footprint of a solute MTBE plume located in Port Hueneme, California. Statistical comparisons of MTBE concentrations, major ions (including cations Ca, Na, K, Mn, Mg, Fe, and Ba; anions including SO_4, NO_3, Cl, and Fl), and water levels from the wells displayed no significant performance differences and no strong systematic variations attributed to well installation method or design. Using the analysis of variance (ANOVA) statistical approach, the authors concluded that spatial and temporal variations in chemical concentrations were considerably larger than variations associated with well type. The Port Hueneme DP well comparison site was incorporated into this project based on the previous observations, the unique and careful experimental design, the analyte type (MTBE), the hydrogeologic attributes of the site, and the personnel and infrastructure supported at the Port Hueneme NETTS.

2.3 Factors Affecting Cost and Performance

The primary factors influencing costs associated with the installation of either DP or conventional wells are directly related to the generation of solid and liquid industrial derived wasted (IDW) and time considerations (Kram *et al.*, 2001).   Time is a significant consideration, especially if one uses the Kram and Farrar Well Design Specification (WDS) approach for well design, as it saves over 50 percent of the installation time when compared to the sampling and grain size distribution via sieve analyses approach described and recommended in ASTM

D5092. Furthermore, since one can install wells using CPT, well installations can be coupled to site characterization efforts, and well designs based on CPT soil classifications and WDS (which is based on ASTM grain size distributions) are optimized and therefore more cost effective, as there is a reduction in the location redundancies, each well location is based on specific data needs for that portion of the plume configuration, and probabilities for well failure are significantly reduced. Drilling spoils are essentially non-existent for DP wells, with the exception being a small amount of soil removed while installing the surface seal and traffic or "Christy" box. Conversely, conventional well installations typically generate a significant volume of soil cuttings. For example, during the installation of the conventional wells at the Port Hueneme site, approximately 40 gallons [5.35 ft^3] of IDW were generated for each conventional well installed to a depth of 20 feet [6.1m] bgs.

Conservative cost savings are illustrated in Table 2-1 (modified from Kram *et al*., 2003). Savings are derived based on total maximum well depth and well diameter. For each category, it was assumed that 10 wells were installed at each location and that all well screens were 5 feet [1.52m] in length. Other considerations included costs for materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for DP well installations range from approximately 32 to 68 percent (Figure 2-6). Highest percentage savings can be derived when using smaller diameter wells at deeper total depths. Users must consider that smaller diameter wells may not be appropriate for some applications (e.g., when a pump is to be used), that deeper wells can be more challenging for DP installation methods, and success will depend upon the soil lithology and resistance to hydraulic or hammer installation techniques.

Table 2-1. Cost Comparison Between DP and Drilled Monitoring Well Installations. Estimates were derived assuming 10 wells per site, each designed with 5-foot [1.52m] screens.

	Direct-Push Wells		Drilled Wells	3/4" Savings	2" Savings
Total Depth	3/4"	2"	2"	3/4"	2"
20	$7,799	$10,254	$15,146	48.5%	32.3%
50	$10,664	$14,575	$28,418	62.5%	48.7%
75	$14,876	$20,543	$46,393	67.9%	55.7%

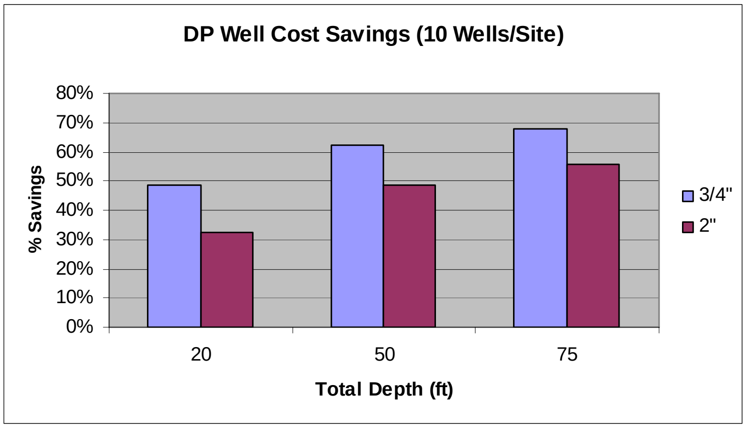


Figure 2-6. Percentage DoD Savings for DP Well Installations Based on Well Diameter and Depth.

When accounting for the total DoD savings due to DP well installations versus conventional drilled wells, several assumptions were used. Since the number of DoD well installations per year is unknown, it was assumed that 500 wells per state are currently installed each year. The authors recognize that this value is not correct, and that it is perhaps overly conservative (e.g., actual number is probably much higher). For instance, at NBVC Port Hueneme alone, several hundred wells were installed per year for several years in a row. Regardless, Figure 2-7 displays the total anticipated DoD savings per year assuming 25,000 DP wells (or 500 per state) are installed per year. Estimates range from approximately $12M to close to $80M per year for DoD alone. Since the majority of DP wells are less than 2 inches [5.08cm] in diameter, the low end DoD cost savings estimate is approximately $20M per year. Using these conservative estimates, industry savings could exceed $500M dollars per year with as few as 6,300 DP wells per state per year.

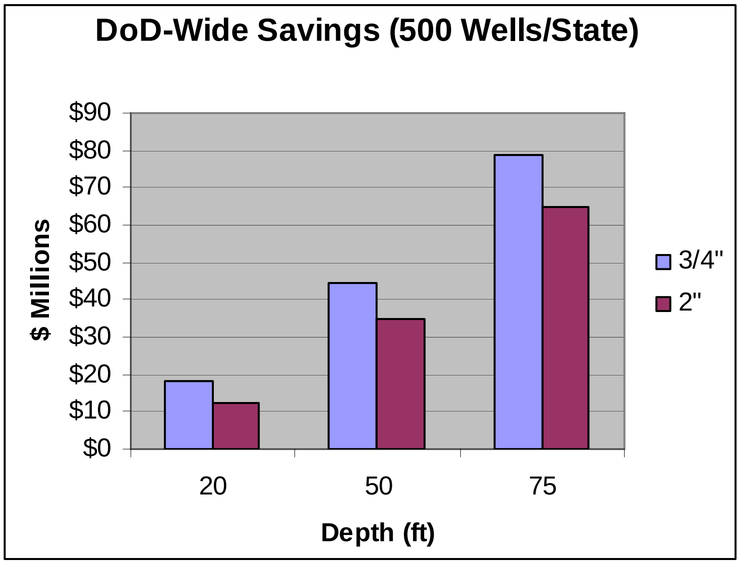


Figure 2-7. Anticipated DoD Annual Savings by DP Well Installations for LTM. Values were derived assuming that 500 DP well installations would be completed per state each year.

During the advisory committee workshop following Phase I of this demonstration, California regulators expressed concern about filter pack design in drilled wells. The primary issues have to deal with the fact that most DP wells are not designed in accordance with ASTM D5092, which requires sieve analyses to determine grain size distributions. Formation candidate screen zone grain size distributions dictate filter pack gradation and subsequently screen slot size. Interestingly, conventional wells are also required to meet these guidelines, yet rarely do installers follow these directives. Instead, in order to avoid the required sampling, sieve, and redeployment steps, drillers typically use a "one-size-fits-all" design that consists of a 20/40 sand pack tremmied to reside adjacent to a 0.010 inch [.03cm] slotted screen section. Silty sand and finer materials can readily pass through this configuration. As a result, well failure becomes possible, and often probable, especially in silt and clay rich formations.

To adequately address regulatory concerns regarding DP well design constraints, Kram and Farrar developed WDS software, which allows the user to determine the appropriate filter pack gradation and slot size requirements based on cone penetrometer soil type descriptors (U.S. Patent 6,317,694). WDS can be determined in real-time, effectively eliminating the need to collect a soil sample, reducing the time required in the field, and allowing for well design and installation during a single deployment. WDS is currently available on the Navy SCAPS system, as it has been integrated into the WinOCPT data acquisition and processing package. When compared to conventional sampling and sieving approaches for proper well design, cost avoidance through use of WDS prior to DP well installation can be significant, often exceeding 50 percent savings. Primary savings drivers consist of reduction in field time and labor due to avoidance of need to collect samples, reduction in laboratory time due to avoidance of need to conduct sieve analyses, and reduction in need for additional remobilization step following laboratory results.

Regulatory and user concerns regarding hydraulic representativeness of DP wells have also been given significant consideration. If DP wells are to be used to replace conventional drilled wells, capabilities for conducting hydraulic tests of the aquifer could become critical project drivers, as site characterization efforts are never complete without an adequate assessment of potentiometric surface and hydraulic conductivity of the aquifer(s) under investigation.

Water levels were closely monitored during each sampling event, with insignificant differences observed between DP wells and conventional drilled monitoring wells. Therefore, potentiometric interpretation will be essentially identical regardless of the well type used. Costs for water level monitoring will also be identical for the various well types.

To address hydraulic conductivity measurement concerns, the team conducted a comprehensive hydraulic comparison at Port Hueneme Cell B in March of 2003 (Bartlett *et al.*, 2004, NFESC Technical Report TR-2252-ENV, Appendix B). The demonstration was comprised of approximately 300 pneumatic slug-in and slug-out tests as well as multiple steady and unsteady state pumping tests performed on five different well types in fifteen different wells. Conclusions included the following:

- Short duration pneumatic slug tests were determined to be a viable approach for determining hydraulic conductivity values in a highly permeable formation. The results of a statistical comparison between the pneumatic slug tests lasting only a few seconds and the steady state pumping tests yielded no statistical difference.
- Hydraulic conductivity values in DP wells were found to be independent of pre-pack design, well radius, induced head, and test method.
- The hydraulic conductivity values determined from the different well types in the B1 and B2 clusters had a mean post development value of 2 by 10^{-2} cm/sec and a standard deviation of 8 by 10^{-3}. The ANOVA analysis indicated there was no statistical difference amongst the pre-pack wells. Furthermore, there was no statistical difference between the pushed no-pack wells and the drilled wells. However, the ANOVA analysis indicated that there was a statistical difference between the latter wells and the pre-pack wells. The variance associated with hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells are largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method. Although development had an impact on the hydraulic conductivity for most of the wells, the impact was ambiguous. Of the 15 wells tested, 10 wells had statistical differences in hydraulic conductivity between pre- and post-development. Of the 10 wells exhibiting differences, 5 wells showed increases in hydraulic conductivities and 5 wells showed decreases.
- Unsteady state, steady state pump, and pneumatic slug tests were shown to be a statistically comparable means of determining hydraulic conductivity analysis in high permeable formations.

Fortuitously, recent advances in aquifer test equipment and rapid data collection capabilities allowed for evaluation of relatively highly permeable soils. Prior to this, pneumatic slug tests

could not typically be performed in soils with hydraulic conductivities greater than approximately 10^{-4} cm/s because response times for highly permeable soils were much faster than measurement time capabilities. Dr. Gary Robbins of the University of Connecticut modified the GeoProbe pneumatic testing device to allow for rapid slug-in and slug-out testing modes, increasing the productivity significantly while enabling users to cross-check their initial tests with a critical quality control measurement. This recent advancement has significant cost advantages, as hydraulic conductivity values can now be measured in highly permeable zones with as little as three seconds of data. As with conventional slug tests, storage coefficient values cannot be derived. For storage values, drawdown observations in adjacent wells are required.

2.4 Advantages and Limitations of the Technology

Table 2-2 lists several of the most important advantages and limitations associated with DP wells when compared to conventional drilled wells. Installing monitoring wells by conventional drilling methods is typically a time consuming and costly component of site characterization and monitoring. It is becoming widely recognized that DP well installations are significantly less costly than conventional drilled well installation approaches. In most formations, DP is minimally intrusive and causes less disturbance of the natural formation than conventional drilling techniques. DP methods are rapid and economical, and often employ more mobile push platforms than conventional drilling vehicles. Worker exposure and IDW disposal costs are reduced because little or no potentially contaminated drill cuttings are generated when wells are installed with direct-push methods. Since many DP wells have a smaller diameter than traditional drilled wells, purge water volumes, sampling time, and indirect waste disposal costs are reduced for most sampling activities. Numerous innovations have been developed for groundwater monitoring through the direct-push casings. For example, by employing packers or multi-level sampling ports, groundwater sampling from multiple zones can be conducted. When coupled with field screening and other site characterization and field analytical approaches afforded by direct-push sensor and sampling techniques, DP well installations afford expedited, comprehensive plume delineation while establishing infrastructure for LTM in a single mobilization. This is consistent with current industry trends towards employing a Triad approach to expedited site characterization.

Table 2-2. Advantages and Limitations of DP Wells (Modified after ITRC).

Advantages	Limitations
• Inexpensive to install, replace and abandon • Minimal waste "cuttings" • Fewer well development wastes • Rapid installation and site characterization • Less worker exposure to contaminants • Representative chemistry and field parameter measurements • Improved landowner relations	• Not applicable when cobbles or consolidated materials are present • Not accepted for LTM in most states • Debate remains regarding aquifer testing capabilities • Well diameter limitations • Pump diameter limitations • Potential for higher turbidity in wells with no filter pack

The installation of DP wells is limited to unconsolidated soils and sediments including clays, silts, sands, and some gravels and cobbles, depending on the push equipment (e.g., heavy CPT trucks can push through harder materials than light trailer mounted rigs). Direct-push methods cannot be used to install monitoring devices in consolidated bedrock and deposits containing significant cobbles and boulders, or in heavily cemented materials. Also, smaller diameter screens and risers do not allow for use of some conventional down-hole pumps for purging or sampling. Although state-by-state approval has been slowly on the rise, most states do not currently accept DP wells for LTM applications. The recent publication of the ITRC Technical Regulatory guide (ITRC, 2006), and the initiation of on-line workshops could lead to more rapid approval.

3.0 DEMONSTRATION DESIGN

3.1 Performance Objectives

The demonstration objectives included performance comparisons between DP wells and conventionally drilled HSA wells with respect to specific field measurements and analyte concentrations. In addition, once statistical analyses were completed, and once these results suggested that DP wells perform comparably to conventional drilled wells, technology transfer was to be pursued through various activities including generation of ASTM DP well construction standards, an ITRC Technical Regulatory guide (comprised of DP well construction descriptions, advantages and limitations of DP well technology, regulatory issues, and a summary of this field demonstration), development of regulatory variance guidance, national workshops, and presentations to conference attendees and regulatory representatives. Table 3-1 summarizes the type of performance objective, performance criteria, expected performance metrics, and whether the performance objectives were met.

Table 3-1. Performance Objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objective Met?
Quantitative	Organic Contaminant and Inorganic Analyte Concentrations	Statistically Significant Agreement based on Percent Variability Attributed to Well Type Categorical Factor; Power of the Statistic	Yes, with few exceptions
Quantitative	Field Parameters	Statistically Significant Agreement based on Percent Variability Attributed to Well Type Categorical Factor; Power of the Statistic	Yes with few exceptions
Quantitative	Detect Versus Non-Detect Organic Contaminant Concentrations	Percent Level of Tolerance	Yes

Quantitative	Hydraulic Property Representation	Statistically Significant Agreement based on Percent Variability Attributed to Well Type Categorical Factor; Power of the Statistic	Yes
Qualitative	Management Decision Consistency	Based on Source Zone, Non-Detect, and Medium Level of Impact/Concentration	Yes; Decision Consistent in All But One Case Believed to be Due to Heterogeneous Distribution of NAPL
Qualitative	Regulatory Approval	Regulatory Support via Standards, Technical Regulatory Guidance, Variance Approvals and Guidance, and Workshops Sponsored by ITRC and Navy RITS	Yes, via ITRC Tech Reg (ITRC, 2006), ASTM Standards Development and Publications, ITRC and Navy Sponsored Workshops, State Approvals for DP Wells and Variances, Overwhelming Industry Support

Several challenges exist when trying to compare conventional wells to drilled wells. For instance, when using conventional drilled wells as experimental controls, the implication is that the conventional wells produce empirically accurate monitoring results. Because there is no universally accepted standard monitoring well or sampling method that produces an absolutely accurate representation of the groundwater, deriving an experimental control is not trivial. This is critical because the primary focus of this study is not to measure the accuracy with which samples from DP wells are representative of the groundwater, but rather to determine whether DP wells produce statistically equivalent results relative to conventionally drilled wells.

In addition to concerns regarding conventionally drilled wells serving as experimental controls, project partners recognized early in the demonstration that heterogeneity with respect to spatial distributions of solute contaminant concentrations and hydraulic conductivity could impart significant levels of variability in the observed results. In other words, if the concentration of an analyte obtained from the control well differed significantly from the concentration obtained from a DP well, the difference could be due to spatial distribution of the concentration in the subsurface and might not necessarily be the result of differences in well type. Since this

heterogeneity is also dynamic, there can also be a temporal impact. For example, during the initial Phase I sampling rounds, water samples were collected and analyzed in triplicate. Within-well concentrations exhibited very low variability, while within-cluster comparisons exhibited statistically significant variability when comparison of the means was conducted using a conventional Student *t*-Test. If only one sampling round was evaluated, observers could conclude that the well types behave differently. Multiple sampling rounds were observed and, while the within-well variabilities remained low, within-cluster means for multiple rounds still exhibited high variability. However, there was no consistency regarding which well type exhibited higher mean values for all sampling rounds. One sampling event reflected a higher mean value in the drilled well representative, while another event exhibited a higher mean value in a DP representative. In order to best address these concerns, an ANOVA statistical approach was adopted, as categorical factors beyond simple well type differences can be incorporated into the data treatment and isolated and ranked based on their contribution to the total observed variability over time. For instance, variabilities associated with spatial heterogeneity, timing, and well screen length and position can be evaluated and weighed against variability due exclusively to well type (i.e., conventional versus DP).

When evaluated over several seasons, researchers can determine whether specific trends exist in the data. For instance, if one particular well type consistently exhibits a higher concentration than another over time, and if it is assumed that the spatial distribution of the subsurface solute concentration is dynamic and over time can exhibit relatively higher and lower concentrations depending upon when a sample event occurs, it may be possible to argue that the wells behave differently. However, if for some events the DP well type exhibits a higher concentration than the control well, then during other events, the control well displays higher concentration, this suggests that observed variability is due more to the subsurface spatial heterogeneity and dynamic characteristics of this heterogeneity than well type design. Furthermore, when considering relative range of concentrations observed in well pairs and clusters, whether or not a management remediation decision would change becomes a critical issue. If the trend in DP wells is that their values consistently lead to the same management recommendations (i.e., detect versus non-detect, above or below action levels, moderate concentration range versus high concentration requiring remediation, etc.) as the corresponding control (i.e., conventional drilled) wells, even if there are statistically significant differences in the concentration values, since the management decision does not change, this is indeed significant, as it suggests that the DP wells meet critical performance goals.

In such a comparison, due to influences on the observations made which cannot be completely controlled, there is no absolute indication of sameness. Instead, the performance objective must be expressed in terms of the maximum acceptable degree of statistical uncertainty that sameness must exist. For this study, the performance objective is acceptance of the null hypothesis that the results from the wells do not differ at the 95 percent confidence level (á=0.025 for a two-tailed test). That is, a p-value of greater than 0.05 would indicate success. In other words, if we can not reject the null hypothesis with better than 95 percent confidence, we must conclude there is no statistically significant bias introduced by substituting DP wells for conventional wells when conducting groundwater monitoring activities. A more detailed statistical description is presented in Section 4.3.1.

3.2 Selecting Test Site(s)

The five sites chosen for this demonstration were selected to satisfy several criteria including the following:

- **Representation of a variety of contaminants and geologic conditions.** Selected sites offered a broad range of common groundwater pollutants (e.g., BTEX, chlorinated solvents, and MTBE) and geological settings ranging from shallow, relatively less heterogeneous sandy aquifers to deep, heterogeneous glacial deposits. The specific contaminants and geologic features of each site are discussed in greater detail in Section 3.3.
- **Representation of multiple regulatory domains.** Selected sites are located in five separate states and four EPA regions.
- **Proximity to study team members.** Selected sites allowed for direct participation and oversight by team members without incurring unnecessarily burdensome travel and logistical expenses. Three of the five selected sites were co-located with team member's duty stations.
- **Leveraging experimental apparatus and sampling support provided by other studies, past and present.** A prior study by AFRL to assess DP well performance utilized 43 DP wells adjacent to conventionally drilled wells at Hanscom AFB. Eight of these existing well pairs were selected for use in this demonstration. A concurrent study by NAVFAC ESC personnel at Port Hueneme included installation of eight multiple-well clusters, all of which were also used for this project. The Navy and Air Force leveraged funds to cover all sampling costs at Port Hueneme and at Dover AFB. During Phase I, selection of Tyndall AFB allowed Air Force team members stationed at the site to perform sampling with significant cost savings. For Phase II, Tyndall sampling was coordinated with support from DNTS personnel.

3.3 Test Site Description

General test site characteristics are presented in Table 3-2. Pairs or clusters of DP wells and conventional drilled wells were installed at each of the sites. For Phase II, some of the pairs were converted to clusters by addition of alternative well design representatives adjacent to the pairs.

Table 3-2. General Test Site Characteristics

Location	Well Pairs/Clusters	Geologic Character	Depth to GW (ft)	Potential Analytes	Max Analyte Concentration (ppb)
CRREL	3 Clusters	Glaciofluvial & Glaciolacustrine	87 - 128	Chloroethenes	43,900
DNTS	6 Clusters	Marine Depositional	15 - 26	Chloroethenes, MTBE, BTEX, Chloroethanes	21,900 108 1,000 93,200
ESC	8 Clusters	Fluvial Deltaic	5 - 12	MTBE	657

HAFB	12 Pairs	Glaciolacustrine	3 - 75	Chloroethenes, BTEX, Chlorobenzenes	8,800 1,300 96.6
TAFB	8 Clusters	Marine Depositional	3 - 8	Chloroethenes, MTBE, BTEX Chloroethanes	4,700 285 4,210 98

Brief site histories, characteristics, maps, illustrations and other site-specific details are provided below.

CRREL

The Army CRREL is a U.S. Army Corps of Engineers laboratory that is now one of seven laboratories in the Corp's Engineering Research and Development Center (ERDC-CRREL). CRREL is located on 30 acres of land, west of and adjacent to State Highway 10, 1.5 miles north of the Town of Hanover, in Grafton County New Hampshire. The site is roughly rectangular in shape and measures approximately 1,360 feet east to west and 970 feet north to south at its maximum extent. Highway 10 forms the eastern boundary of the site, and the Connecticut River is located west of the CRREL property, separated from the site by a stump dump yard and domestic refuse storage area. The CRREL site contains seven major buildings and other smaller support structures, including a pump house for five production wells and a groundwater remediation building. A small storm water detention pond (100 feet by 50 feet) is located at the southwest corner of the site.

The first building on the CRREL site (the main laboratory) was constructed in the early 1960s. Prior to that time, the land was used for agriculture although gravel was also mined on the western edge of the site. CRREL's mission is to perform basic and applied research in snow, ice, and frozen ground, and to provide the Corps of Engineers, the Army, and the Department of Defense with practical scientific and engineering research on cold related problems. Because CRREL's mission is the cold, the laboratory contains a cold-room complex. In the early years (1960 to 1987), TCE was the primary refrigerant used in the cooling systems. In addition, the site contained an Ice Well (located near the main laboratory) that was used to test ice drills. This well extended to bedrock and was encased with a refrigeration system that was used to freeze the well. Groundwater has become contaminated with TCE as a result of at least two major accidents and several minor spills. The CRREL site contained a large underground storage tank and a 10,000 gallon above-ground storage tank. Both tanks contained TCE. TCE leaks were commonplace in the earlier years. Leaks from pump seals, cold-room piping, and replacement coolant piping were all identified as possible sources of contamination. Also, TCE drums were known to leak and had been dumped in a gravel pit. In 1970, the above-ground storage tank exploded and 3,000 gallons of TCE were spilled on the ground. This spill was subsequently hosed into the storm sewer by the fire department. TCE was also released to bedrock when an ice drill penetrated the refrigerant coil (containing TCE) in the wall of the ice well.

The geology of the CRREL site consists of two main geologic units: the overburden sequence and the bedrock. The overburden consists entirely of Glaciofluvial and Glaciolacustrine sediments. Glaciofluvial sediments at CRREL were deposited in a major esker that passes

through the western border of this site. This esker is 50 miles long, and extends from Bradford, Vermont (north of CRREL) to White River Junction (south of CRREL). The esker crosses the Connecticut River approximately 3,500 feet north of CRREL and continues south on the New Hampshire side of the river for several miles. Based upon topographical expression and geologic logs, the esker is approximately 400 feet wide at CRREL. Immediately southwest of the CRREL boundary, the esker is exposed and forms a ridge. Within the property boundaries of CRREL, the esker deposits are buried beneath younger glaciolacustrine silt and clay. Boring logs associated with monitoring wells at CRREL have shown that the contact between the overlying and adjacent lacustrine sediment is extremely sharp. The thickness of the esker deposits is approximately 60 feet, and where present, rest directly on bedrock. The esker deposits have NCRS classifications of SP and SW and consist of densely packed fine to coarse sand. The sand typically is a mixture of quartz, feldspar, and dark metamorphic and igneous rock fragment grains.

Glaciolacustrine sediments at CRREL were deposited during the formation of a glacial lake (Lake Hitchcock) that formed as melt water from the glacial retreat was dammed by a moraine in the Connecticut Valley near Middletown, Connecticut. In general, the lacustrine stratigraphy consists of thin beds ranging in composition between clay and fine sand, interbedded with thicker beds of sand. The varied, thin beds represent seasonal deposition cycles, while thicker sand beds were deposited in a deltaic setting from sources near the lake.

Sediment of glaciolacustrine origin is present at all locations at the CRREL site. West of the lower terrace access road, the lacustrine deposits overlie the esker. At the remainder of the site, the lacustrine deposits comprise the entire overburden stratigraphy. The stratigraphy of the lacustrine sediment consists of three main units: a fine silty sand, a silt, and a silty clay.

Based upon the available borehole and geophysical data, the majority of the site is located on top of a buried asymmetric bedrock valley. The bedrock consists of deformed metasedimentary rock. Bedrock coring at five locations at CRREL indicates that the bedrock beneath CRREL consists of amphibolite and paragneiss. This site is located immediately east of a major normal fault, known at the Ammonoosic Fault, which parallels the Connecticut River in the vicinity of CRREL. Structural fabrics in the rocks include the dominant foliation and one set of conjugate fractures oriented at a high angle to the dominant foliation. This fault is defined by the realignment, zonation, and recrystallization of minor groups. Fractures are annealed by recrystallized quartz, calcite, and pyrite.

Across most of the site, the water table is located within the glaciolacustrine units. However, at the western edge of the site, the water table occurs in bedrock. The hydrostratigraphic units fall into two main categories: unconsolidated deposits and bedrock. Groundwater, over most of the site occurs within the fine silty sand (SM) unit and the fine to coarse sand (SP/SW) deposits of the esker. However, beneath the lower terrace access road, overburden groundwater also occurs in the fine sand silt (ML) unit. Groundwater occurs in the bedrock throughout the CRREL site, and movement through the bedrock occurs along discrete fractures.

The lacustrine clay unit (CL) is located above the groundwater table and contains perched water, especially on the lower terrace near the northern boundary and the sandy to clayey silt (SM) at

the center of the site along the lower terrace access road. The occurrence of perched water may be due to several factors including: the presence of a drainage swale along the east side of the access road, leaks in storm sewer lines located along the west side of the access road, or the residual effects of an intermittent stream that was buried during construction.

DNTS

Dover Air Force Base is located in the Coastal Plain Physiographic Province, and is underlain by unconsolidated clastic sedimentary deposits. These deposits are comprised of medium to fine sands, which contain lenses of gravels, silts, and clays and are referred to as the Columbia Formation. Deposits in this area are between 36 and 47 feet thick. Underlying the Columbia Formation is an approximately 28-feet thick unit of gray, firm, dense marine clay forming an aquitard and referred to as the Calvert Formation. The unconfined surficial aquifer is called the Columbia Aquifer. Hydraulic conductivity within the Columbia ranges from 3 by 10^{-3} to 1 by 10^{-2} cm/s.

The locations selected for this study at Dover AFB represent three distinctly different contaminant plumes – chloroethenes from multiple degreasing operations in the West Management Unit, BTEX compounds from JP-4 releases at the South Tank Farm in the South Management Unit, and a more recently discovered MTBE plume extending from the northwest/southeast (NW/SE) runway to the Base boundary in the West Management Unit. Each plume described is in the surficial aquifer (Columbia) underlying Dover AFB. This aquifer has two distinct hydrogeologic flow systems that are differentiated as either the shallow or deep zone.

Well Pairs 354 and 237, and Clusters 235 and 236, are located within a massive chlorinated solvent plume resulting from several different sources, but together form a 1.5 mile long plume. The primary source areas are located in the industrial areas adjacent to the NW/SE runway and are largely due to the waste processing practices used at the time for activities such as airplane engine degreasing. The resultant plume extends beneath Route 1 towards the Saint Jones River. Concentrations within the plume have been recorded as high as 20,000 μg/L. Figure 3-1 depicts the location of DNTS well clusters.

Well Pair 53S is located in the South Management Unit downgradient of a former tank farm that became the source of a BTEX plume (Figure 3-2). The tank farm consisted of three aboveground storage tanks (each with a capacity of greater than 100,000 gallons) used to store JP-4, and three oil/water separators located outside of the concrete containment berm surrounding the tanks. All tanks and associated JP-4 pipelines were removed from service in 1989. The highest total BTEX concentrations identified in this plume exceed 5,000 μg/L.

The remaining well pair 337 is located at the toe of an MTBE plume that extends west from the north-south flight line in the West Management Unit, intersecting the Dover National Test Site (Figure 3-3). This plume was more recently identified (1999) and delineated in 2001. The highest concentrations in this plume approach 2000 μg/L.

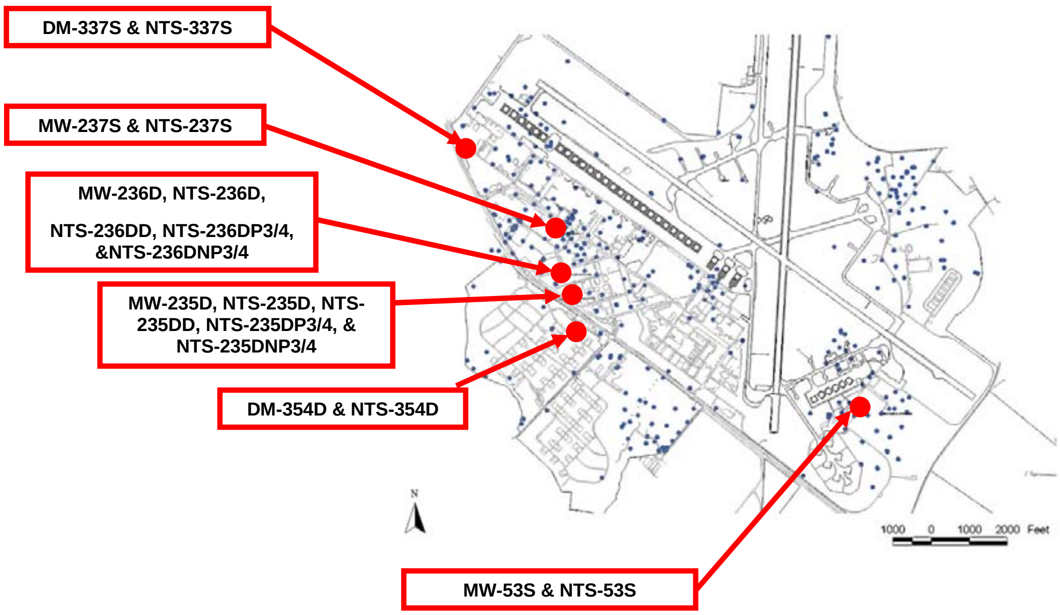


Figure 3-1. Dover National Test Site Well Clusters and Pairs.

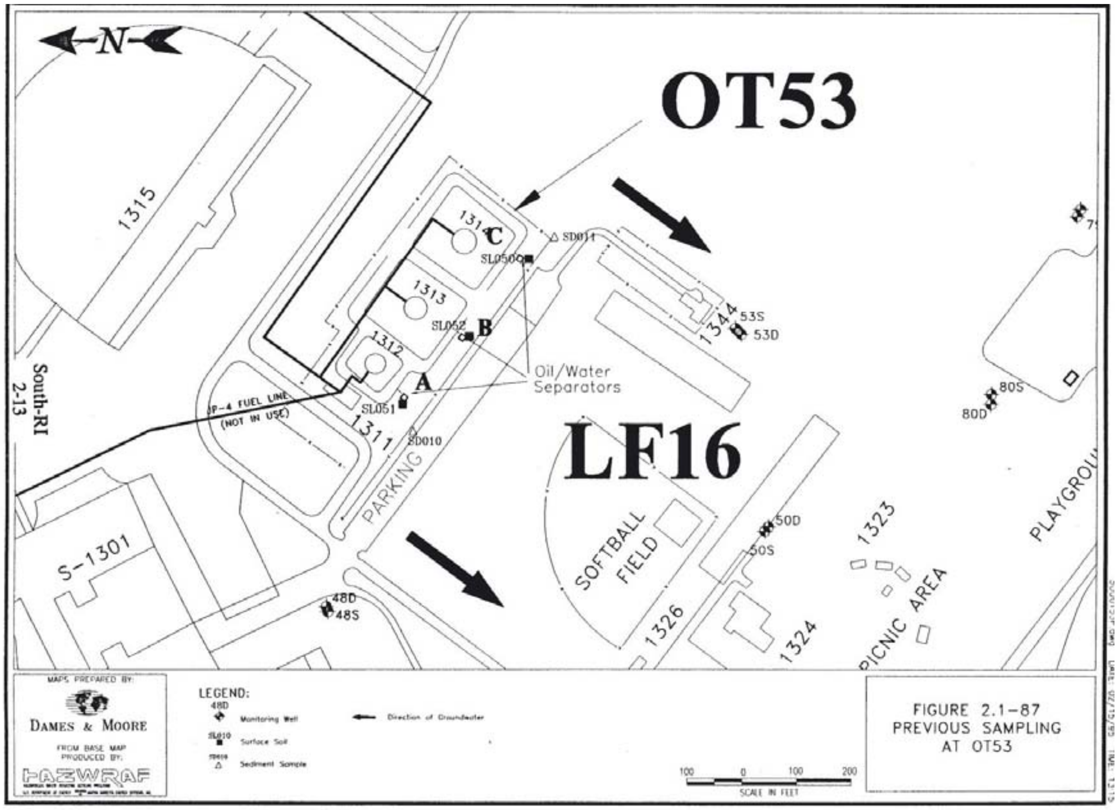


Figure 3-2. Former South Tank Farm.

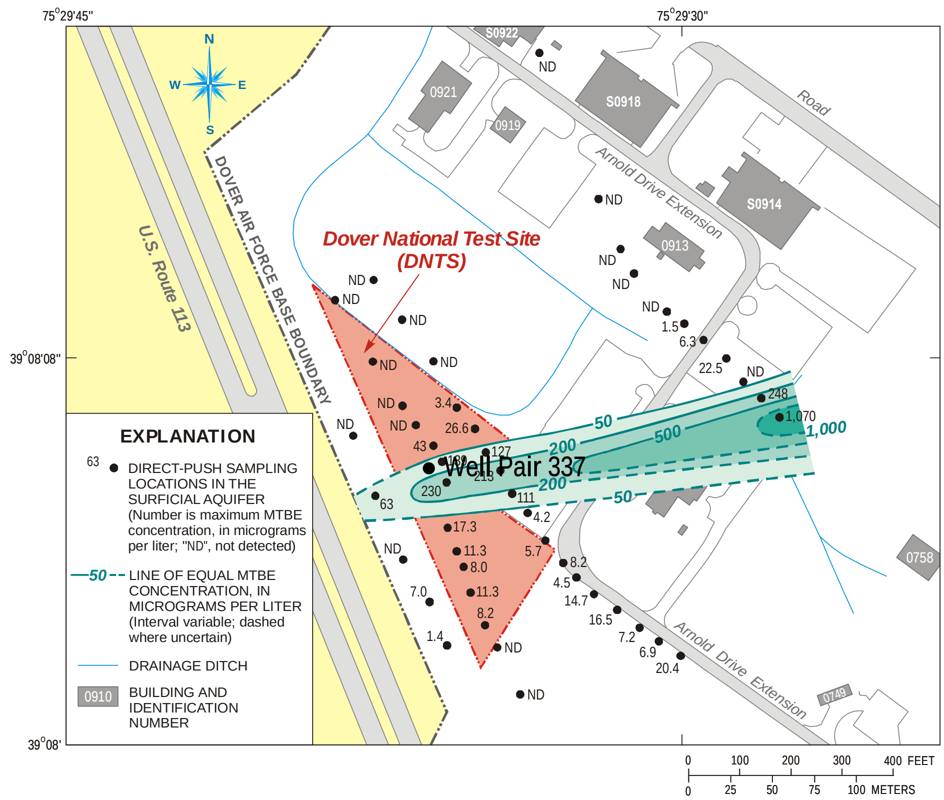


Figure 3-3. MTBE Plume intersecting Dover National Test Site.

NBVC Port Hueneme

The demonstration was conducted within an MTBE plume located at NBVC Port Hueneme, California. According to NBVC personnel, gasoline was released from the underground storage tanks (USTs) and fuel distribution lines at the Navy Exchange (NEX) automobile service station in 1984. A large source zone and associated dissolved contaminant plume have resulted in MTBE concentrations as high as 35,000 µg/l in the shallow, semi-confined sand and silt aquifer.

One of the two evaluation cells (Cell A) was installed downgradient of the plume in the direction of migration along Track 13 just west of the Daewoo lot. The other cell (Cell B) was installed in a moderately contaminated portion of the plume between the Daewoo lot and Building 401 (Figure 3-4). The cells were constructed in areas covered by asphalt. The two test locations consisted of footprints approximately 10 feet by 10 feet [3.048 m by 3.048 m]. During Phase I, the plume migrated through the Cell A well clusters. Figures in Section 3.5 display more details regarding the Cell B well cluster layout. For additional information, see Kram *et al.*, 2000.

Although the site soil was not homogeneous, this effort did not address large ranges of hydrogeologic conditions. The "semi-perched" aquifer zone consisted of fluvial-deltaic sediments approximately 25 feet (4.6 m) thick in the vicinity of the site. The uppermost silty sands graded into more sand and silty sand at depths ranging from approximately 6.0 to 25 feet [1.8 to 4.6m] below ground surface (bgs) depending upon the location within the plume footprint. The unconfined water table ranged from 5 to 12 feet [1.5 to 3.7m] bgs, depending on

the location along the plume, the distance from the coastline, and the most recent climatic, barometric, and tidal conditions. The saturated aquifer thickness ranged from approximately 15 to 20 feet [4.6 to 6.1m]. Anticipated groundwater elevations in the two evaluation cells typically ranged between 5 and 7 feet [1.5 to 2.1m] bgs. Tidal, climatic, and barometric factors could have contributed to the water table elevation in the vicinity of the proposed evaluation cells. Mean hydraulic conductivity in the most permeable zones in the cells ranged from 6.3 by 10^{-4} to 6.4 by 10^{-2} cm/s, and tended to be higher in the deeper portions of the aquifer where the sand units tended to be relatively more coarse. The average linear groundwater velocity in the unconfined aquifer ranged from approximately 0.5 to 1.5 feet [0.15 to 0.46m] per day.

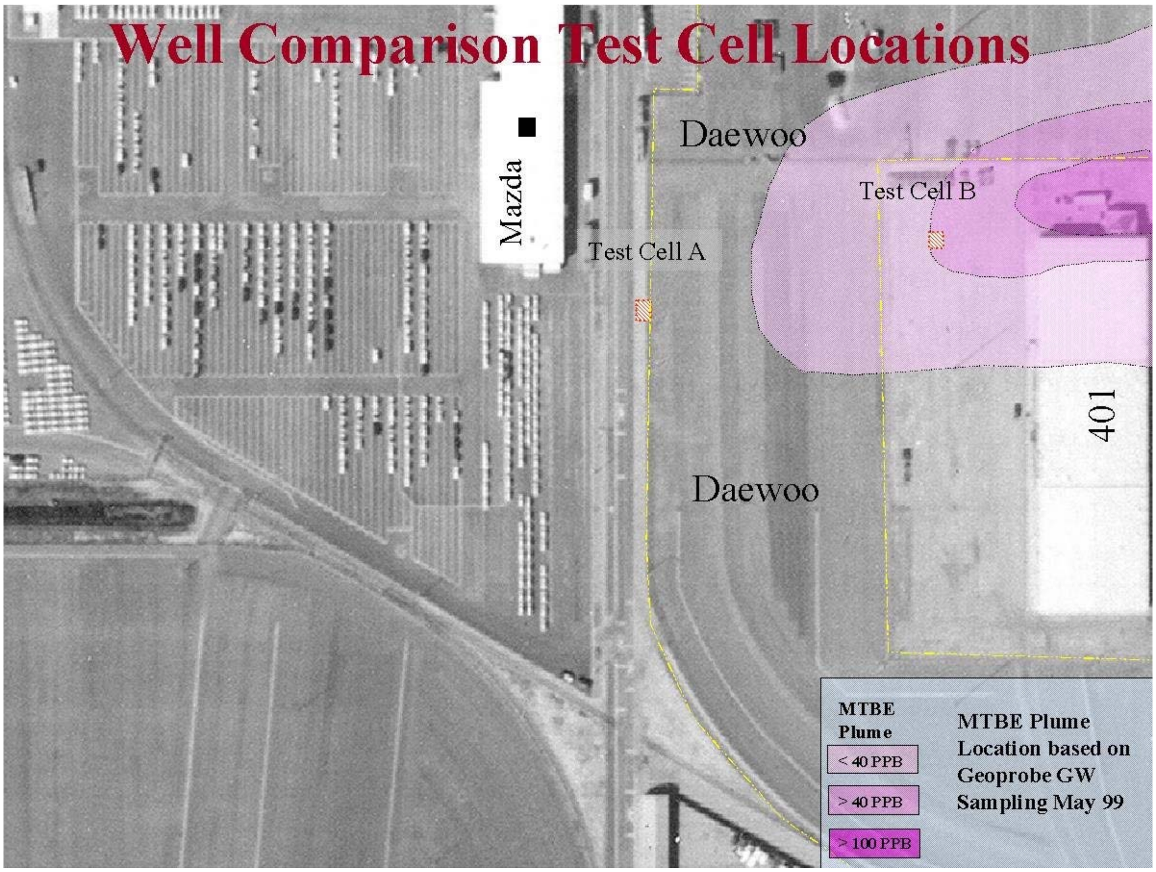


Figure 3-4. Locations of NAVFAC ESC (formerly NFESC) Well Comparison Test Cells A and B as of May 1999.

Hanscom Air Force Base (AFB)

Hanscom AFB and Hanscom Field are situated approximately 14 miles northwest of Boston, Massachusetts, in the towns of Bedford, Concord, and Lincoln. Hanscom Field is a civilian airport currently operated by the Massachusetts Port Authority (Massport). Hanscom AFB is a military installation located adjacent to and southeast of the airfield. The wells sampled in this demonstration were located in Sites 1, 2, and 21, which were located two operable units, OU-1 (Sites 1 and 2) and OU-3 (Site 21).

Prior to 1974, Hanscom Field was used as a military airport by the Air Force. During this time, hazardous substances were generated by support operations and disposed of at different sites on the airfield. In addition, flammable materials were ignited and extinguished during fire training exercises performed at selected sites on the airfield. The sites contained in OU-1 include the following: Sites 1 and 5 were fire training areas, Site 2 was a waste disposal area for paint, and Site 3 was a jet fuel residue/tank sludge disposal area (Figure 3-5). Site 21 is located on Hanscom AFB southeast of the airfield in OU-3 (just outside of OU-1) and was formerly used for fuel and gasoline storage and distribution.

A remedial investigation was conducted in 1987 (Haley and Aldrich, Inc., 1988) to assess potential soil and groundwater contamination in OU-1. Volatile organic compounds were detected in the groundwater in three separate aquifers. In response to these findings, a groundwater treatment facility was installed at the airfield where groundwater was collected from trenches located at Sites 1, 2, and 3, and four bedrock interceptor wells located along the northern Hanscom Field property boundary. Treated water was then routed to a drainage ditch, which discharges into the wetlands to the north, and/or routed to recharge basins at Sites 2 and 3, where it is reintroduced to the groundwater.

Between the years 1945 and 1973, Site 21 was used for jet fuel and aviation gasoline and during the 1970s the site was only used for heating and fuel oils. During this period, several spills were identified in the vicinity of former buildings and areas of this site. In 1990 the storage tanks were removed and the land is now in use as a general storage area. In September of 1995, a soil vapor extraction and passive groundwater collection system began operation to remove subsurface contamination.

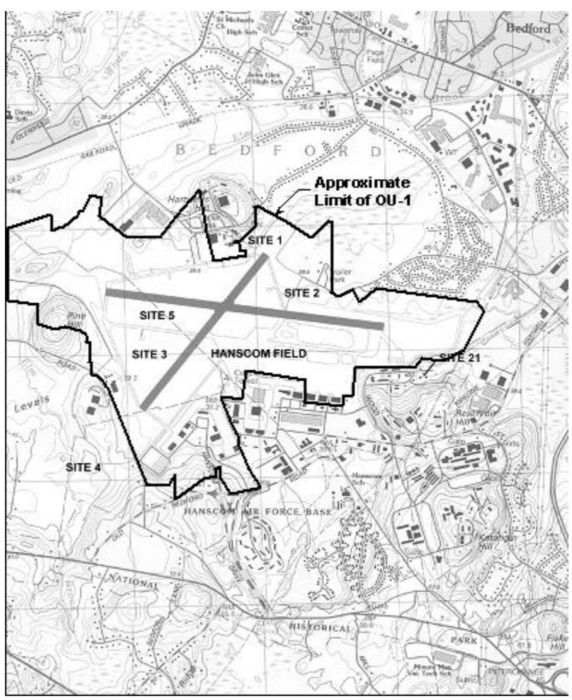


Figure 3-5. Hanscom AFB and Hanscom Field test site locations.

Hanscom Field and AFB are located on a flat-lying plain with a general relief of less than 10 feet over a distance of approximately 3 miles. This feature is an ancient lake basin that was formed and subsequently filled in by sediment during the last phase of glaciation in New England. The plain extends beyond OU-1 to the north and west. To the south and east, this plain is bounded near the limit of OU-1 by low-lying hills of glacial till and gravel. Other topographic features include Hartswell Hill and Pine Hill. These are till-covered, isolated hills located at the northern and western boundaries of OU-1, respectively. The hills provide a relief of approximately 100-feet above the surrounding plain.

The principal drainage features in the vicinity of OU-1 are the Shawsheen River, which originates in the east end of the air field and flows toward the northeast, and Elm Brook, which is located west of the airfield and ultimately flows northwest and into the Shawsheen River.

Test borings completed during an Installation Restoration Program have identified three principal soil deposits underlying OU-1. From upper to lower, these soils are an outwash section, a lacustrine section, and a till section. The till section is deposited above bedrock, which consists primarily of granite but some zones of gneiss and quartz diorite have been encountered. Most borings have encountered numerous fractures, some filled with silt. No predominant direction of fracturing has been identified. It is not known how deep into the bedrock significant groundwater flow persists.

The upper most outwash section measures 0 feet to 33 feet in thickness and consists primarily of fine sand. Locally this unit is composed of medium to coarse sand with lesser amounts of gravel. The underlying lacustrine section consists of interbedded silt, clay, and fine sand. The unit varies in thickness from 0 feet to 60 feet. Beneath the lacustrine section is a till deposit which locally grades into a lower outwash unit. This unit measures from 0 feet to 88 feet in thickness.

These geological units define three separate aquifers. The outwash section comprises the area's near-surface unconfined aquifer. The till section, positioned beneath a thick sequence of lacustrine clay, silt and fine sand, forms a lower, semi-confined aquifer. A third aquifer has been encountered by monitoring wells installed into bedrock.

Tyndall Air Force Base (TAFB)

TAFB is located in Bay County of the south-central Florida Panhandle. The county is situated in the Gulf Coastal Lowlands portion of the Gulf Coastal Plain regional physiographic province. The lowlands are characterized by features such as beach ridges, barrier islands, lagoons, estuaries, and offshore bars. These features are remnants of the eustatic sea level fluctuations which occurred during the Pleistocene Epoch. Topography of the region is generally flat with areas of elevation less than 60 feet above mean sea level (MSL). Surface runoff is relatively slow due to the shallow groundwater conditions which exist beneath the Base. For areas of the Base north of Highway 98, surface runoff empties into man-made drain ways, natural creeks, and bayous which eventually empty into East Bay. Precipitation falling on portions of the Base south and west of Highway 98 drains into St. Andrews Bay and the Gulf of Mexico.

The region surrounding Tyndall AFB has a humid, subtropical climate, characterized by long, hot summers and short, mild winters. The climate is influenced by the Gulf of Mexico and the

Caribbean Sea. The Gulf of Mexico contributes to the mild winters and is responsible for the relatively high humidities. The annual temperature at the Base is 70°F, with an average monthly high of 89°F in July and August and an average low of 46°F in January. Monthly average relative humidity ranges from 71 to 77 percent.
The reported yearly evapotranspiration is 12.8 inches, however, the measurement may be higher, depending on vegetative cover. Florida is characterized by a wet summer season and a dry winter season. The rainy season occurs from June through September, with an average rainfall of 6.57 inches. The average annual precipitation is 55.19 inches, with the lowest rainfall in May and the highest in July.
Wells used in this study are located within three distinct areas on Tyndall AFB at sites designated as SS026, SA150, and SS015. Figure 3-6 illustrates the relative location of the three sites and the respective well designations discussed below.

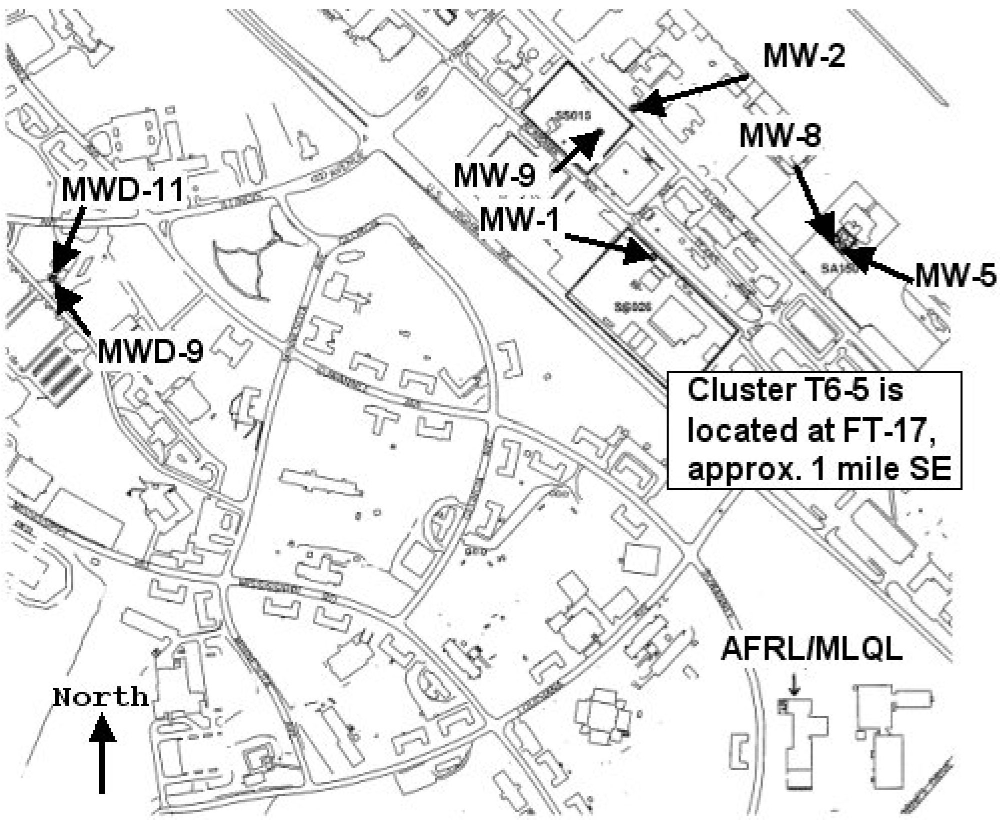


Figure 3-6. Tyndall AFB Study Areas.

Well cluster MW-1 is located within Site SS026, the Vehicle Maintenance Area (Building 560 Area), located in the west-central portion of TAFB. The Site is topographically flat, asphalt and grass covered, comprising an area of approximately 600 feet by 350 feet and sloping gently toward the south. The SS026 Site includes: six buildings; two 10,000 gallon underground storage tanks (USTs), a hazardous waste accumulation area adjacent to the north perimeter of Building 559 (former heating oil UST location); a waste oil tank located along the southern perimeter of Building 561; and two oil/water separators located adjacent to building perimeters and connected to floor drains and sumps within Site buildings. Daily operations at SS026

involved vehicle maintenance including general maintenance, repair, body work, washing, and fuel distribution. The Site has operated in the same capacity since the 1950s. Recently, USTs formerly used to store heating oil have been removed from the area adjacent to the north wall of Building 559, and this area is currently used as a hazardous waste accumulation point. Groundwater beneath this site was encountered at depths ranging from approximately 5.6 to 6.5 feet below ground surface and groundwater in the shallow portion of the Surficial Aquifer flows primarily toward the north to northeast. The hydraulic gradient beneath the site was determined to be 0.011 ft/ft. The hydraulic conductivities calculated from wells screened in the shallow portion of the Surficial Aquifer ranged from 13.94 ft/day to 156.26 ft/day. Assuming a porosity of 0.20, the average pore velocity of groundwater beneath the site was estimated to range from 0.75 ft/day to 8.65 ft/day.

Well clusters MW-5 and MW-8 are within Site SA150, located adjacent to Building 150, which is used to house a back-up generator for emergency power. A concrete secondary containment was built adjacent to Building 150 to contain a 500-gallon aboveground storage tank (AST) used to store diesel fuel used by the emergency generator. SA150 was operational for approximately 20 years. The 500-gallon AST was removed from the Site in February 1995 by Air Force Civil Engineering. The associated ancillary piping was abandoned in place. On February 22, 1995, the Environmental Office at TAFB sent a "Discharge Report Form" to the Florida Department of Environmental Regulation to notify the agency that a diesel fuel leak of approximately 250 gallons had been discovered during inventory control of Building 150. The source of the leak was believed to be the underground ancillary piping. Groundwater beneath this site was encountered at a depth of approximately 4 feet below ground surface. Based upon relative survey data, groundwater beneath the site appears to flow generally toward the north to northeast. The hydraulic gradient beneath the site was determined to be 0.0116 ft/ft. The hydraulic conductivity calculated from one rising head slug test was determined to be 0.5976 ft/day. Assuming an effective porosity of 0.25, the average linear velocity of groundwater beneath the site was estimated to be 0.0278 ft/day (10.1344 ft/year).

Well clusters MW-2 and MW-9 are within Site SS015, which is a flat, rectangular shaped grass lot located in the east-central portion of TAFB, adjacent to the flight line. Building 509, used for the production of liquid oxygen, is located to the west of the Site. A general purpose aircraft shop (Building 522) and parking lot are located south of the Site. An active oil/water separator is located across Florida Avenue. The Site, which began operation in 1943, consisted of fourteen USTs, one AST, associated fuel pipelines and dispenser islands, with a total capacity of approximately 500,000 gallons. The Site, a fuel supply area for the flight line, contained storage tanks for jet fuel (JP-4), aviation fuel (AVGAS), diesel fuel, and motor vehicle fuel (MOGAS). All underground storage and aboveground storage tanks, as well as service islands were removed from the site between 1985 and 1987. Connecting lines associated with site operations were drained and abandoned in place. Sludge and water removal from the Former POL Area B tanks was conducted every three to five years. The sludge, described as mostly water with rust, sediment and small amounts of fuel, was allowed to weather for four to six weeks in shallow on-site trenches which were subsequently backfilled. The water table at this site occurs at a depth of 2 to 5 feet bgs, depending upon the season. In the shallow portion on the surficial aquifer, the groundwater flow direction appears to be toward the north-northeast. The average horizontal flow gradient across the site was 0.018 ft/ft, with gradients increasing toward Florida Avenue

and decreasing near the flight line. The differences in gradient generally mirror changes in the topographic surface. The groundwater flow direction at intermediate depths of the surficial aquifer appears to be toward the east. Horizontal hydraulic gradients in this intermediate portion averaged 0.002 ft/ft. In-situ borehole permeability tests (slug tests) yielded hydraulic conductivities for the shallow surficial aquifer of about 4 to 25 ft/day, and similar results were found at intermediate depths of 2.5 to 25 ft/day.

Well clusters MWD-9 and MWD-11 are within SS019, which is an active Air Force Base Exchange service station (BX Service Station). Site SS019 has served as the main service and fueling station from 1948 to present and is located in the southwest central portion of TAFB. In 1948, a former tank pit was installed approximately 100 feet south of the Shoppette (Building No. 968) and contained USTs which stored leaded and unleaded gasoline. In 1967, these USTs were removed and replaced with new underground tanks. In 1983, these USTs were closed in place. After the closure of the old USTs, three new 10,000-gallon capacity USTs, which are currently in use, were installed in a separate tank pit located east of the dispenser island. One of the USTs was installed with a fill pipe directly over the tank. The two remaining tanks had remote fill ports installed approximately 20 feet from the tanks. At a later date, a new set of remote fill ports and piping were installed parallel to the original fill pipes. The original pipes were not removed or plugged at that time. In 1987, a release occurred due to overfill at the location of the original remote fill lines. The two original remote fills were abandoned and direct fill ports were subsequently installed on the two USTs. In May 1994, approximately one cubic yard of petroleum impacted soil was removed from the site. The soil was subsequently thermally treated at a permitted facility.

Several environmental investigations performed at the site indicated that groundwater in the surficial aquifer was impacted with petroleum-related compounds (i.e., primarily BTEX [benzene, toluene, ethylbenzene, and total xylenes] and total recoverable petroleum hydrocarbons [TRPH]). The site is being addressed under a Petroleum Contamination Agreement based on applicable Florida petroleum regulations (FAC 62-770). Florida regulators view all aquifers as potential drinking water sources and therefore apply drinking water standards to this site.

3.4 Pre-Demonstration Testing and Analysis

A prior study by AFRL to assess DP well performance utilized 43 DP wells adjacent to conventionally drilled wells at Hanscom AFB. Eight of these existing well pairs were selected for use in the study. A concurrent study by NAVFAC ESC personnel at Port Hueneme (Kram *et al.*, 2000) included installation of eight multiple-well clusters, all of which were also used for this project. Both investigations concluded that DP wells performed comparably with conventional drilled wells at their respective sites throughout the timeframe of investigation.

3.5 Testing and Evaluation Plan

3.5.1 Demonstration Installation and Start-Up

Site-specific details regarding well locations, well designs, and site preparation activities are presented below. While DNTS, Hanscom, and TAFB were comprised of wells from previous investigative activities, CRREL and NAVFAC ESC wells were specifically installed for comparison of DP wells to conventional drilled wells.

CRREL

The three pre-existing conventionally-installed monitoring wells selected for this study were MW 9, MW 10, and MW 11 (Figure 3-7). Each conventional well was constructed with 4-inch (internal) diameter schedule 40 PVC casing and screen. The depth of the top of the screens in these wells ranged from 106.5 to 126.5 feet. The PVC slotted screens were 10 feet in length with a 0.01-inch slot size. In 2000 (for Phase I), ½-inch diameter DP wells were installed in close proximity to each of the three conventional wells. These wells were made with schedule 80 PVC casing and screen and had a 9-foot screen with the same slot size as the conventional well and a Geoprobe pre-pack filter pack. Information on these wells can be found in Table 3-3. In 2002 (for Phase II), a ¾-inch DP well was installed adjacent to each of the three conventional monitoring wells. These DP wells were constructed with schedule 80 PVC casing and screen, and each well had a 10-foot screen with a Geoprobe pre-pack filter pack.

All DP wells were installed with a truck-mounted model 6600 Geoprobe unit following the manufacturer's standard operating procedure for well installation. For the first ½-inch diameter DP well installed at CRREL (at Site 11), 3.25-inch OD probe rods were used to conduct soil sampling (down to a depth of 100 feet) with a dual tube soil sampling system (DT-32). Drive rods 2.125 inches in diameter were then advanced to the final depth of the well (116 feet bgs). Once the rods were pushed to the desired depth, casing and pre-packed screen was installed within the drive rods and the rods were retracted to allow the natural formation to collapse above the screens. After formation collapse occurred, bentonite slurry was prepared and the Geoprobe GS-500 grout machine was used to pump the slurry into the annulus of the 2.125-inch rods until they were full of grout. The slurry was installed with a 0.25-inch ID nylon tremmie tube from the bottom up. The 2.125-inch drive rods were tripped out of the bore hole at that time. Tremmie grouting of the remaining annulus of the 3.25-inch rods was completed the following Monday with a 25 percent solids bentonite slurry.

Because the 6600 Geoprobe unit was able to penetrate the formation relatively easily with the 3.25-inch rods, the field team decided to use a more typical method for installing all the subsequent DP wells. For these wells, 2.125-inch drive rods with expendable drive points were advanced directly through the formation without sampling or telescoping the larger diameter rods. This significantly accelerated well installation (Table 3-4). Installation of the casing and screens and completion of these wells was similar to that previously described.

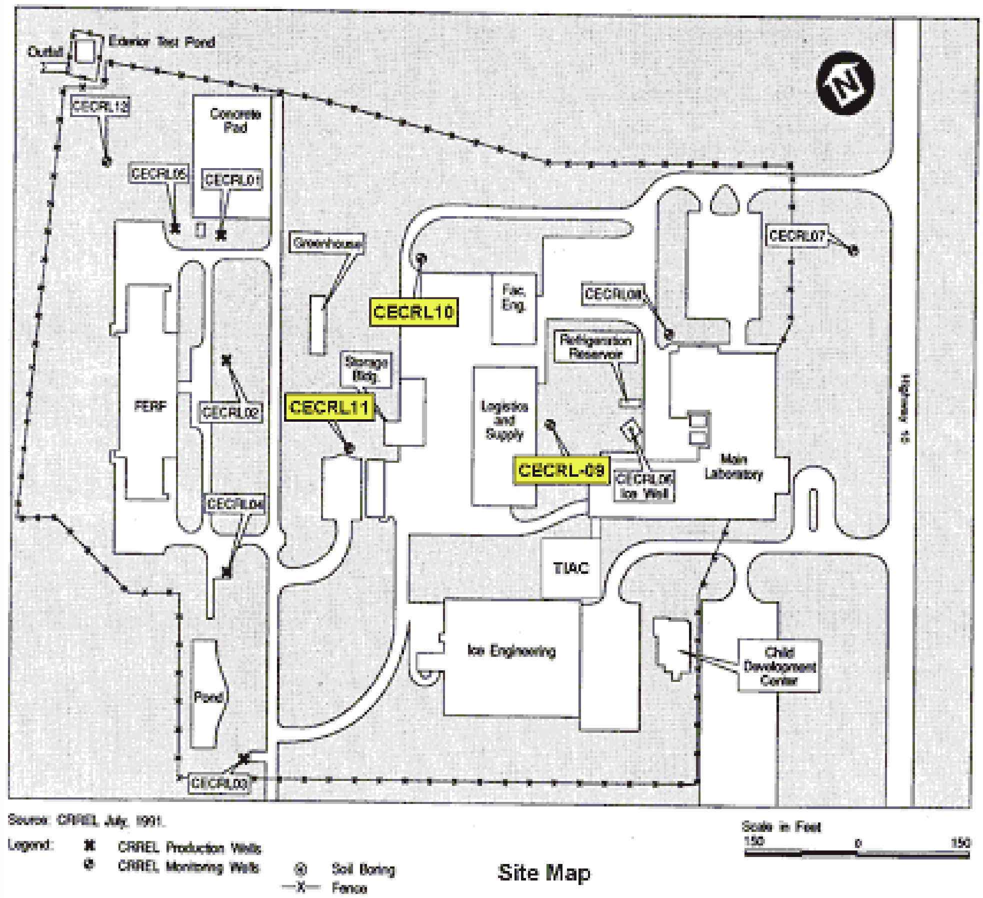


Figure 3-7. CRREL Well Location Map, Phase II.

Table 3-3. Summary of CRREL well construction information

Location	Well type	Year Installed	Casing material	Well diameter [1] (in.)	Well Depth (ft.)	Top of screen (ft. bgs)	Bottom of screen (ft. bgs)	Screen length (ft.)	Screen slot size	Filter Pack
9	HSA	1992	PVC	4	139.0	126.5	136.5	10.0	0.010 in.	# 2 sand
	DP	2000	PVC	1/2	138.5	129.0	138.0	9.0	0.010 in.	20/40 silica sand
	DP	2002	PVC	3/4	140.0	127.0	137.0	10.0	0.010 in.	20/40 silica sand
10	HSA	1992	PVC	4	129.0	117.0	127.0	10.0	0.010 in.	# 2 sand
	DP	2000	PVC	1/2	128.0	117.5	126.5	9.0	0.010 in.	20/40 silica sand
	DP	2002	PVC	3/4	127.3	117.0	127.0	10.0	0.010 in.	20/40 silica sand
11	HSA	1992	PVC	4	118.5	106.5	116.5	10.0	0.010 in.	# 2 sand
	DP	2000	PVC	1/2	116.0	105.5	114.5	9.0	0.010 in.	20/40 silica sand
	DP	2002	PVC	3/4	117.0	106.5	116.5	10.0	0.010 in.	20/40 silica sand
[1] internal diameter										

Table 3-4. CRREL Accelerated Installation Well Construction Details

Location	Well type	Year Installed	Well ID (in.)	Well Depth (ft.)	Time for advancement	Time for well installation & grouting
9	HSA	1992	4	139.0		
	DP	2000	1/2	138.5	80 min.*	2 hr.
	DP	2002	3/4	140.0	61 min.*	7 hr.
10	HSA	1992	4	129.0		
	DP	2000	1/2	128.0	65 min.*	3 hr.
	DP	2002	3/4	127.3	45 min.	4.3 hr.
11	HSA	1992	4			
	DP	2000	1/2	116.0	16.5 hr**	4 hr.
	DP	2002	3/4	117.0	55 min.*	4 & 3/4 hr.

* Using 2.125-inch rods only

**Using 3.25-inch rods to collect soil samples down to 100 ft. and then using 2.125-inch rods to depth

DNTS

Prior to selecting the locations to be used in the demonstration, historical data from existing wells located different plumes were reviewed. Ultimately, six wells with significant historical data representing a range of contaminants and concentrations were selected. Each well was 2-inches in diameter and constructed using HSA methods within the Columbia Aquifer. Original well logs from each well were evaluated and noted such that any additional wells constructed adjacent to them would be duplicated in terms of screen intervals, slot size, and sand pack. Other pre-demonstration activities included piezocone measurements to confirm original soil boring descriptions and collection and analysis of groundwater samples to confirm historical data.

Phase I of the demonstration entailed the installation of new wells adjacent to each of the six locations chosen for the demonstration using direct-push methods. A 10-ton trailer mounted CPT rig using 1.75-inch diameter rods was used to install the wells to the same depth as the existing well. Screen length and slot size was duplicated, however the DP wells did not have sand packs around the screen; rather these wells were pushed directly into the formation (exposed screen). The drive point used at the bottom of the screen created the borehole as the well was advanced; hence the formation is in direct contact with the well screen. Typical construction details are depicted in Figure 3-8.

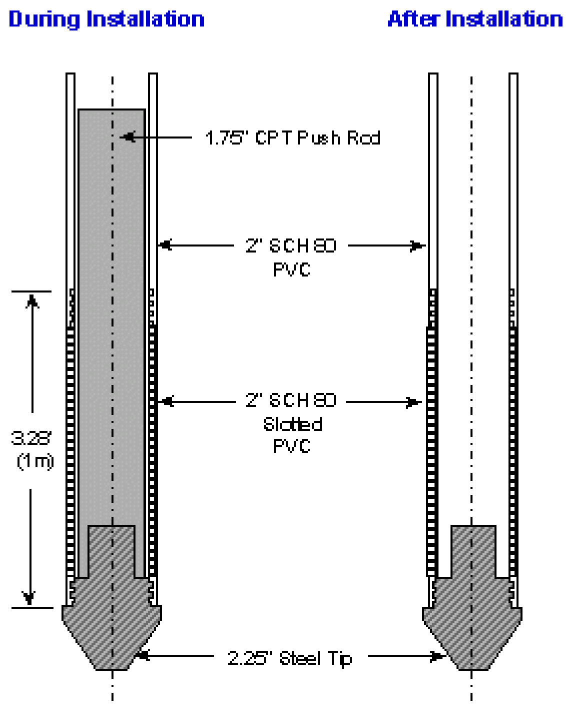


Figure 3-8. Typical DNTS DP Well Construction Details.

Additional wells were added for Phase II of the demonstration to address differences in data between wells of either the same or different construction, thus demonstrating the effects of spatial heterogeneity between wells of any construction. Three additional wells were added to two of the six well pairs to form clusters of five wells. Locations 235 and 236 each had another conventional HSA well installed to mimic the original well construction; a 0.75 inch diameter DP well with a pre-pack; and a 0.75 inch diameter DP well without a pre-pack. Screen slot sizes for all wells were designed at 0.02 inches (the same as the original wells installed). Screen lengths and locations were all consistent with the original well.

The three additional wells were installed using a Geoprobe 6600 series dual purpose Geoprobe rig. This equipment was capable of installing the additional conventional well using a 4.25-inch ID hollow stem auger and the DP wells using 3.25-inch OD drive rods. The pre-pack design for the additional 0.75-inch diameter well was also designed to mimic the original well construction, including a 0.02-inch slot and bentonite seal just above the screen interval. Well construction details for all wells are listed in Table 3-5, where 2-inch HSAS represents conventional well and sand pack, 2-inch DP represents quasi-static installation with no pre-pack, ¾-inch DP NP represents no pre-pack and 3/4-inch DP represents DP wells with pre-packs.

Table 3-5. DNTS Well Construction Details.

Dover NTS			Screen		
Well ID	Type	Type Key	Top	Bot	Len
DM-53S	2" HSA,	1	13.0	23.0	10.0
NTS-53S	2" DP	2	13.1	23.0	9.8
DM-235D	2" HSA,	1	43.0	53.0	10.0
NTS-235D	2" DP	2	40.6	50.4	9.9
NTS-235D (new)	2" DP	2	43.2	53.8	10.6
NTS-235DD	2" HSA,	1	43.3	53.3	10.0
NTS-235DNP 3/4	3/4" DP	3	42.7	52.7	10.0
NTS-235DP 3/4	3/4" DP	4	43.2	53.2	10.0
MW-236D	2" HSA,	1	34.7	45.0	10.3
NTS-236D	2" DP	2	35.1	44.9	9.8
NTS-236DD	2" HSA,	1	35.0	45.0	10.0
NTS-236DNP 3/4	3/4" DP	3	35.0	45.0	10.0
NTS-236DP 3/4	3/4" DP	4	35.0	45.0	10.0
MW-237S	2" HSA,	1	8.4	18.5	10.1
NTS-237S	2" DP	2	8.6	18.4	9.8
DM-337S	2" HSA,	1	26.0	36.0	10.0
NTS-337S	2" DP	2	26.2	36.1	9.8
DM-354D	2" HSA,	1	30.8	40.8	10.0
NTS-354D	2" DP	2	30.8	40.7	9.8

NBVC Port Hueneme

Pre-demonstration field efforts included piezocone measurements to determine soil type classifications, collection of and analysis of core samples, and collection and analysis of groundwater samples from selected depths to determine MTBE solution plume configuration. Laboratory efforts included chemical analysis of water samples, determination of permeability for selected core samples, and determination of grain size distribution for selected samples. Piezocone soil type classifications and grain size distribution results were used to design the cluster wells, allowing for specification of well screen depths, filter pack gradation, and slot size

based on ASTM D5092. Permeability tests were used to select appropriate well screen depth ranges, as the emphasis was to focus on zones dominated by advective fluxes (e.g., high permeability strata), while reducing sampling from zones potentially impacted more by diffusive fluxes (e.g., low permeability zones). Figure 3-9 illustrates penetrometer soil classification logs, boring logs, grain size distribution results, and permeability test results used to design Cell B. These efforts are described in more detail in Kram *et al.*, 2000.

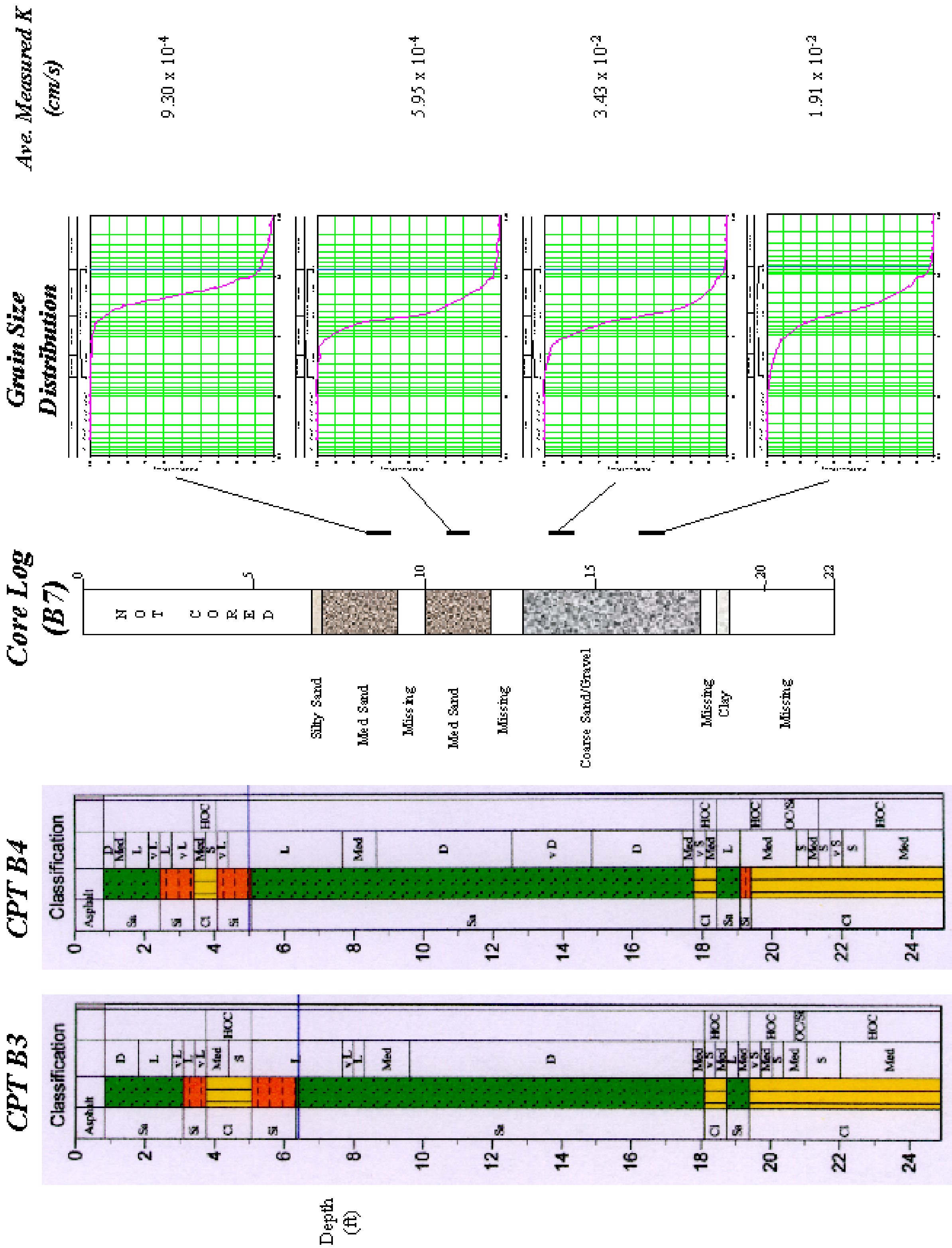


Figure 3-9. Soil classification logs, boring logs, grain size distribution and average permeability values for Evaluation Cell B (after Kram *et al*., 2001).

Phase I maps of the well clusters are presented in Figures 3-10 and 3-11. From February 8 to February 14, 2000, a total of 32 wells were installed in the 2 cells. Twelve wells were installed in Cell A, while a total of 20 wells were installed in Cell B. Prior to installing the wells for Cell A, an asphalt cap was fabricated to prohibit runoff from entering the wells. The drilled wells were installed using a Mobile B-61 hollow stem auger drill rig. All DP wells were installed using a Precision SD-1 direct-push rig. Drilled well filter packs were installed using a tremmie method and sealed in accordance with ASTM D5092. All DP wells with filter packs consist of pre-pack filter packs and expandable bentonite seals. The pre-pack jackets are comprised of inner and outer cylinders of 65-mesh stainless steel filled with sand and fit over the PVC screened sections. The 3/4-inch [1.91cm] jackets have a 1.4-inch [3.56cm] outer diameter. The 2-inch [5.08cm] jackets have a 2.8-inch [7.11cm] outer diameter. All wells were completed to the surface and protected with traffic boxes and keyed-alike (one key fits all) locks.

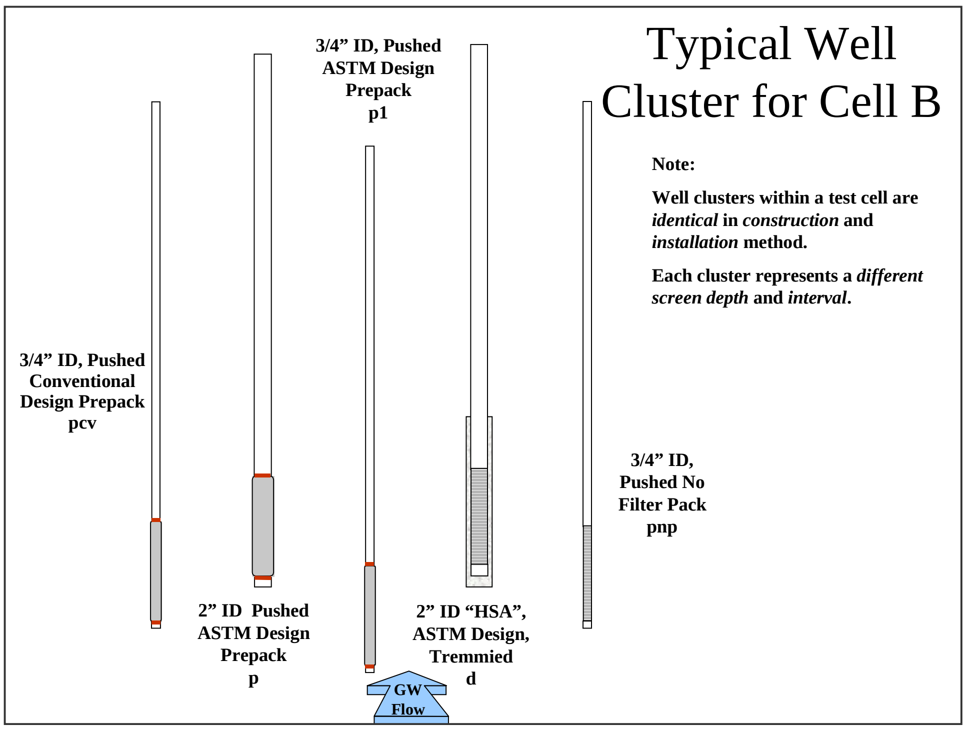


Figure 3-10. Well Cluster Representations for Cell B, Phase I.

Cluster	Screen Length	Screen Interval
B1	2 ft.	10 to 12 ft.
B2	5 ft.	7 to 12 ft.
B3	2 ft.	16 to 18 ft.
B4	5 ft	12.5 to 17.5 ft.

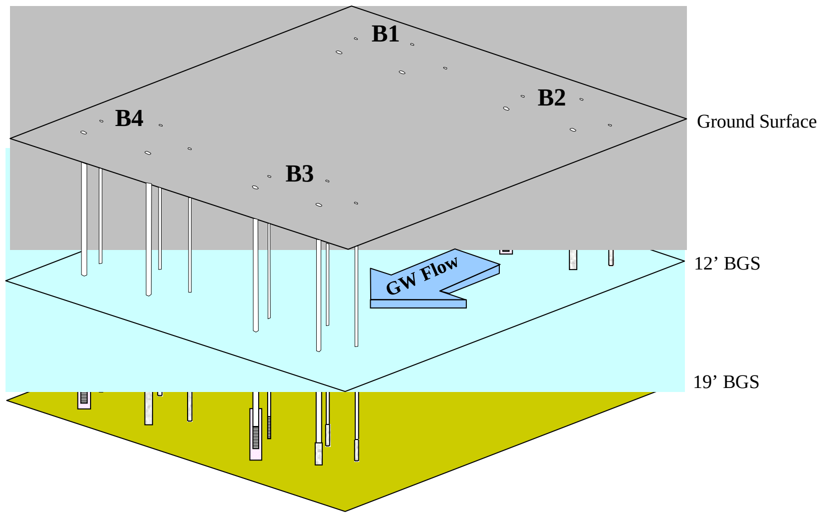


Figure 3-11. Cell B Layout, Phase I.

Well screen depth ranges for each of the clusters in each cell were determined using several factors. Since short screen lengths are expected to yield more comparable and representative solute concentration data on a localized scale, each well was constructed with either a 2- or 5-foot [0.61 or 1.52m] screen length and included a 6-inch [1.27cm] sediment sump. With one exception, the center of each screen for each cluster was set at the most permeable depth. The one exception included the deep clusters for Cell B. Although the 13.5- to 14.5-foot [4.11 to 4.42m] zone displayed relatively higher permeability, the screens were set to encompass the 16- to 17-foot [4.89- to 5.18m] depth range. This was done so that the 5-foot [1.52m] screen lengths for the shallow and deep clusters would not overlap. Although the direct-push screening samples showed non-detectable levels for the 16-foot [4.89m] depth, the differences in permeability between the 14-foot [4.27m] and 16-foot [4.89m] zones were considered negligible when recognizing that the screens span 2- or 5-foot [0.61 or 1.52m] depth ranges. Well clusters (consisting of five wells each for Cell B, and three wells each for Cell A) were grouped by screen length and depth range.

Specific well screen design (filter pack and slot size) was determined using several criteria. To evaluate performance of wells adhering to the ASTM specifications (ASTM D5092), grain size distribution curves were used to determine filter pack grain size and corresponding slot size recommendations. For Cell A, each of the wells was designed using ASTM specifications. For Cell B, two additional well designs were also employed. To evaluate the performance of wells most commonly installed by drillers, a generic “conventional” well design consisting of 20 to 40 sand pack mesh surrounding 0.010-inch [0.25mm] slotted schedule 40 PVC pipe was used as one of the alternatives in each of the well clusters in Cell B. To evaluate performance of non-pack

wells that are often installed by direct-push equipment operators, an additional set of wells consisting of 0.010-inch [0.25mm] slotted schedule 40 PVC pipe was installed without a filter pack in each of the clusters in Cell B.

For Cell A, four clusters were installed, each consisting of the following three types of wells:

3/4-Inch Diameter Pushed Wells – ASTM Specifications (#1 wells)

2-Inch Diameter Pushed Wells – ASTM Specifications (#2 wells)

2-Inch Diameter Drilled Wells – ASTM Specifications (#3 wells)

For Cell B, four clusters were installed (Figure 3-9), each consisting of the following five types of wells:

1. 3/4-Inch Diameter Pushed Wells – No Filter Pack (#1 wells)
2. 3/4-Inch Diameter Pushed Wells – ASTM Specifications (#2 wells)
3. 3/4-Inch Diameter Pushed Wells – “Conventional” (0.010 slot; 20-40 sand) (#3 wells)
4. 2-Inch Diameter Pushed Wells – ASTM Specifications (#4 wells)
5. 2-Inch Diameter Drilled Wells – ASTM Specifications (#5 wells)

Table 3-6 presents well construction details. Nomenclature for each cluster was established to preserve relationships between wells, emplacement methods, and evaluation cells. The first two symbols in each well name refer to the cluster they belong to. For instance, each A1 well belongs to the A1 cluster. The “p” and “d” refer to emplacement method (pushed versus drilled, respectively), “pcv” refers to pushed conventional, and “pnp” refers to pushed no-pack designs. Although small diameter push wells consist of 3/4-inch inner diameter riser pipes, a “1” is used in the name to signify “1-inch wells” (a common name for these types of wells).

Table 3-6. NAVFAC ESC Well Construction Details, Phase I

Cell (Cluster #)	Well Names	Inner Diameter (in.)	Emplacement Method	Screen Depth Range (ft)	Filter Pack Mesh	Slot Size (in.)
A (1)	A1p1 (A1-1)	3/4	Pushed	9.5 - 11.5	20 to 40	0.010
A (1)	A1p (A1-2)	2	Pushed	9.5 - 11.5	20 to 40	0.010
A (1)	A1d (A1-3)	2	Drilled	9.5 - 11.5	20 to 40	0.010
A (2)	A2p1 (A2-1)	3/4	Pushed	7 – 12	20 to 40	0.010
A (2)	A2p (A2-2)	2	Pushed	7 – 12	20 to 40	0.010
A (2)	A2d (A2-3)	2	Drilled	7 – 12	20 to 40	0.010
A (3)	A3p1 (A3-1)	3/4	Pushed	17 – 19	10 to 20	0.030
A (3)	A3p (A3-2)	2	Pushed	17 – 19	10 to 20	0.030

A (3)	A3d (A3-3)	2	Drilled	17 – 19	10 to 20	0.030
A (4)	A4p1 (A4-1)	3/4	Pushed	14 – 19	10 to 20	0.030
A (4)	A4p (A4-2)	2	Pushed	14 – 19	10 to 20	0.030
A (4)	A4d (A4-3)	2	Drilled	14 – 19	10 to 20	0.030
B (1)	B1pnp (B1-1)	3/4	Pushed	10 – 12	No-pack	0.010
B (1)	B1p1 (B1-2)	3/4	Pushed	10 – 12	10 to 20	0.020
B (1)	B1pcv (B1-3)	3/4	Pushed	10 –12	20 to 40	0.010
B (1)	B1p (B1-4)	2	Pushed	10 – 12	10 to 20	0.020
B (1)	B1d (B1-5)	2	Drilled	10 – 12	10 to 20	0.020
B (2)	B2pnp (B2-1)	3/4	Pushed	7 – 12	No-pack	0.010
B (2)	B2p1 (B2-2)	3/4	Pushed	7 – 12	10 to 20	0.020
B (2)	B2pcv (B2-3)	3/4	Pushed	7 – 12	20 to 40	0.010
B (2)	B2p (B2-4)	2	Pushed	7 – 12	10 to 20	0.020
B (2)	B2d (B2-5)	2	Drilled	7 – 12	10 to 20	0.020
B (3)	B3pnp (B3-1)	3/4	Pushed	16 – 18	No-pack	0.010
B (3)	B3p1 (B3-2)	3/4	Pushed	16 – 18	10 to 20	0.020
B (3)	B3pcv (B3-3)	3/4	Pushed	16 – 18	20 to 40	0.010
B (3)	B3p (B3-4)	2	Pushed	16 – 18	10 to 20	0.020
B (3)	B3d (B3-5)	2	Drilled	16 – 18	10 to 20	0.020
B (4)	B4pnp (B4-1)	3/4	Pushed	12.5 - 17.5	No-pack	0.010
B (4)	B4p1 (B4-2)	3/4	Pushed	12.5 - 17.5	10 to 20	0.020
B (4)	B4pcv (B4-3)	3/4	Pushed	12.5 - 17.5	20 to 40	0.010
B (4)	B4p (B4-4)	2	Pushed	12.5 - 17.5	10 to 20	0.020
B (4)	B4d (B4-5)	2	Drilled	12.5 - 17.5	10 to 20	0.020

For the Phase II effort, two additional well designs were added to two selected clusters, for a total of four additional wells. One additional 2-inch [5.08cm] diameter ASTM specified drilled well and one additional ¾-inch [1.91cm] pre-pack ASTM specified DP well were installed in Cluster B1 (2 foot [0.61m] screens) and Cluster B4 (5 foot [1.52m] screens). These duplicate wells were installed to determine whether solute concentration spatial variability impacts the concentration observations in closely spaced wells. To help reduce costs, only Cell B was investigated during Phase II of this demonstration effort. The Phase II revised well Layout is presented in Figure 3-12.

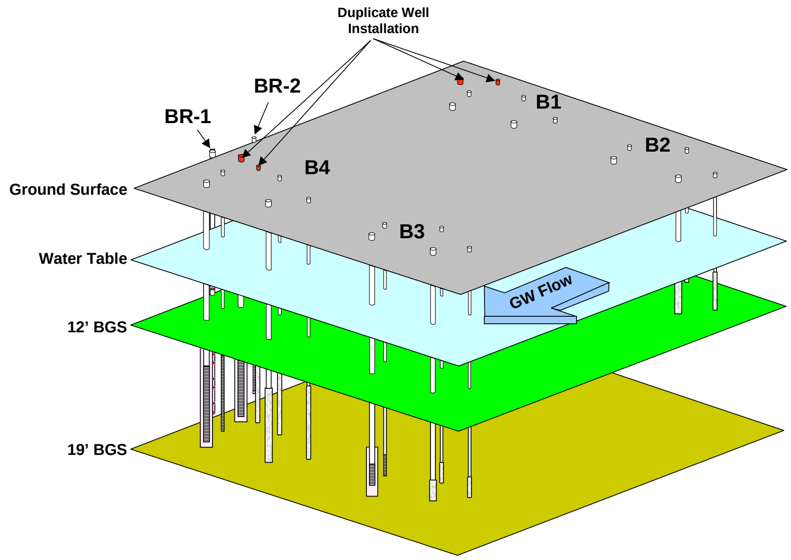


Figure 3-12. Cell B Layout, Phase II.

Hanscom Air Force Base

Figures 3-13 and 3-14 show the location of all the conventional wells at Sites 1, 2, and 21. Twelve pairs of DP and conventional wells were selected for sampling from among 43 pairs that had been established during a previous assessment of DP well technology. To minimize any spatial variability, the CPT-installed DP wells were located as closely as practicable to the existing auger-drilled wells (within 5 to 10 feet). In addition, screened intervals were matched as closely as possible in the vertical dimension so that the sampling depth was consistent within the well pairs. The conventional HSA wells were constructed with 2-inch diameter schedule-40 PVC casing, and the screens had 0.010-inch or 0.020-inch slot sizes (Table 3-7). The DP wells were constructed with 2-inch diameter schedule 80 PVC casing, and all screens had a slot size of 0.020 inch (Table 3-8). The larger slot size was selected for the DP wells because well development is more effective and to help compensate for the potentially lower permeability of the formation contacting the DP wells. For most of the well pairs used in this demonstration, the screen length for the DP and conventional HSA wells were 10 feet in length and the elevation of the screens matched closely. However, this was not always the case. There were two pairs of wells with approximately 5-foot screens (OW2-2, OW2-6), one well pair with approximately 25-foot screens (RAP2-4S), and one well pair where the DP well screen was approximately 5 feet in length but the conventional well had an approximately15-foot screen (RAP2-2T). For the DP wells at Site 2, a silt trap was installed to help maintain the effective screen area on these wells.

Before individual wells were selected for the study, each of the contaminated sites at Hanscom AFB and Field were evaluated against the data quality objectives. Sites 1, 2, and 21 were selected based on the range of contaminants present at the sites, distribution of the wells, and ease of access to these sites. Although 12 well pairs were sampled during the course of this investigation, only 8 pairs of wells were sampled during any 1 sampling event. Thus, not all the wells were sampled each time.

Table 3-7. Summary of well construction for conventional wells at the Hanscom sites

	General Construction				**Screen Construction**				
Monitoring	**Total**	**Depth to**	**Well**	**Well**	**Top**	**Bottom**			**Screen**
Well	**Depth**	**Water**	**Dia.**	**Mat'l**	**Depth**	**Depth**	**Length**	**Aquifer**	**Size**
No.	(ft. bgs)	(ft. bgs)	(inches)	Riser/Screen	(ft. bgs)	(ft. bgs)	(feet)		(inches)
Site No. 1									
B103	15.0	13.18	2	PVC	5.0	15.0	10.0	L/T	0.010
RAP2-2T	75.3	10.13	2	PVC	60.1	75.3	15.2	T	0.020
RAP2-4S	25.0	7.88	2	PVC	0.0	25.0	25.0	S/L	0.020
Site No. 2									
B107	14.0	10.03	2	PVC	4.0	14.0	10.0	S	0.010
OW2-2	20.0	9.12	2	PVC	15.0	20.0	5.0	S	NA
OW2-6	20.0	9.64	2	PVC	15.0	20.0	5.0	S	NA
RFW-11	17.2	11.66	2	PVC	7.2	17.2	10.0	S	0.020
Site No. 21									
MWZ-4	20.0	13.03	2	PVC	10.0	20.0	10.0	S/T	
MWZ-6	18.5	7.23	2	PVC	8.5	18.5	10.0	S/T	
MWZ-11	22.0	8.39	2	PVC	12.0	22.0	10.0	L/T	
MWZ-23	19.0	16.9	2	PVC	9.0	19.0	10.0	L	

Table 3-8. Summary of well construction for Hanscom DP wells.

	Installation	Total Well	Silt Trap	Depth to	Well	Well	Top of	Bottom	Screen	Screen	Tip
Well	**Date**	**Depth**	**(sump)**	**Water**	**Diameter**	**Material**	**Screen**	**of Screen**	**Length**	**Slot Size**	**Material**
Identification		feet (b.g.s.)	feet	feet (b.g.s.)	inches		feet (b.g.s.)	feet (b.g.s.)	feet	inches	
Site 1											
B103	Jan-97	15.00	none	13.47	2	PVC	5.16	15.00	9.84	0.02	nylon
RAP2-2T	Dec-96	62.19	none	8.80	2	PVC	55.63	62.19	6.56	0.02	steel
RAP2-4S	Dec-96	24.52	none	6.32	2	PVC	4.84	24.52	19.68	0.02	nylon
Site 2											
B107	Dec-96	17.21	3.28	11.12	2	PVC	4.09	13.93	9.84	0.02	nylon
OW2-2	Dec-96	23.39	3.28	12.18	2	PVC	16.83	20.11	3.28	0.02	s.s.
OW2-6	Dec-96	23.10	3.28	11.04	2	PVC	13.26	19.82	6.56	0.02	nylon
RFW-11	Dec-96	20.34	3.28	11.79	2	PVC	7.22	17.06	9.84	0.02	nylon
Site 21											
MWZ-4	Feb-97	17.90	none	13.77	2	PVC	8.06	17.90	9.84	0.02	nylon
MWZ-6	Feb-97	18.78	none	8.51	2	PVC	8.94	18.78	9.84	0.02	steel
MWZ-11	Feb-97	19.93	none	11.17	2	PVC	10.09	19.93	9.84	0.02	steel

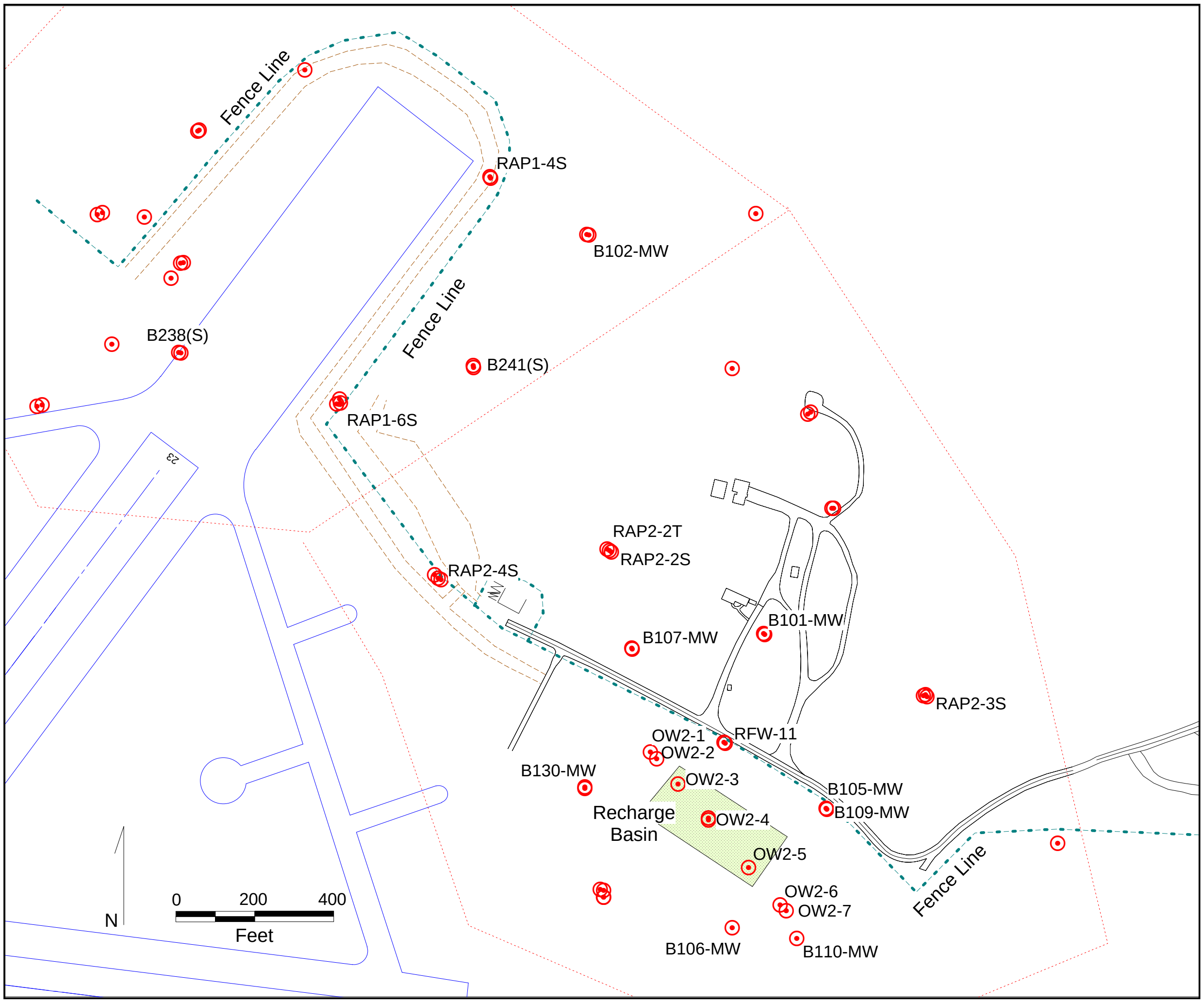


Figure 3-13. Map of Sites 1 & 2 showing the locations of the original Hanscom HSA monitoring wells.

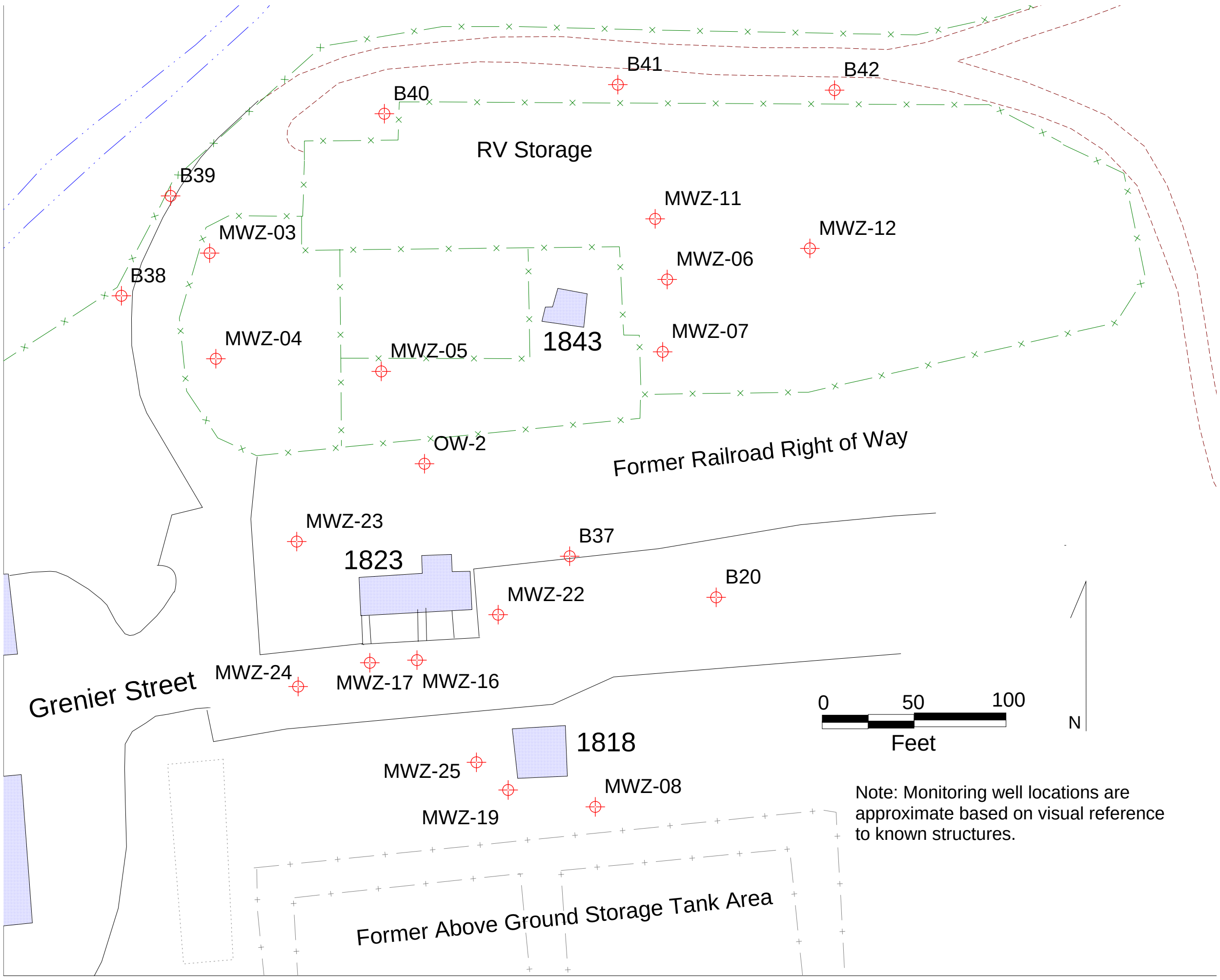


Figure 3-14. Map of Hanscom Site 21 showing the locations of the original HSA monitoring wells.

The existing, conventionally-installed monitoring wells were not developed under this study, since these wells were previously developed and were part of a separate, on-going water quality study.

TAFB

Study locations on Tyndall AFB were selected based on a range of data collected from existing wells at the facility. Of those surveyed, eight existing well locations were chosen for this demonstration. Phase I of the demonstration entailed the pairing of each well with a DP installed 2-inch diameter exposed screen well (no sand pack), a 1.0-inch diameter pre-pack DP well, and a 0.5-inch diameter pre-pack DP well. The 2-inch diameter DP wells were installed with the Army's SCAPS rig using 1.75-inch diameter rods. A two-inch diameter pilot hole was first created using an oversize tip on the end of the string of rods. After creating a pilot hole, the rods were pulled from the formation, the oversized tip was removed, and the rods were set inside of the screen and casing, resting on a drive point forming the bottom of the well. The screen and

casing were pushed into the pilot hole to the desired depth. The rods were then retrieved from inside the well leaving the casing in direct contact with the formation.

The 1.0-inch diameter pre-packed wells and some of the 0.5-inch diameter wells were installed with a Geoprobe Model 66DT probing unit using 3.25-inch OD by 2.5-inch ID probe rods. The remaining 0.5-inch diameter wells were installed with a pick-up truck mounted Geoprobe Model 5410 unit using 2.125-inch OD by 1.5-inch ID probe rods. All Geoprobe installed wells were installed following the Geoprobe Systems Standard Operating Procedure. Table 3-9 presents a summary of the Tyndall well construction details.

Table 3-9. Tyndall Well Construction Details.

Tyndall AFB
Well Construction Type Key:
1. 2" "HSA" Conventional Sand Pack
2. 1.5" DP (Quasi-Static Installation)
3. 1" DP (Hammer Installation), Pre-pack
4. 1/2" DP (Hammer Installation), Pre-pack

Tyndall AFB			Screen		
Well ID	Type	Type Key	Top	Bot	Len
MW-1-C	2" "HSA"	1	3.0	13.0	10.0
MW-1-P05	0.5" DP	4	4.0	13.0	9.0
MW-1-P10	1" DP	3	3.0	13.0	10.0
MW-1-P15	1.5" DP	2	2.6	12.5	9.9
MW-2-C	2" "HSA"	1	26.0	35.4	9.4
MW-2-P05	0.5" DP	4	27.0	36.0	9.0
MW-2-P10	1" DP	3	26.0	36.0	10.0
MW-2-P15	1.5" DP	2	25.7	35.6	9.9
MW-5-C	2" "HSA"	1	1.5	11.5	10.0
MW-5-P05	0.5" DP	4	2.5	11.5	9.0
MW-5-P10	1" DP	3	1.5	11.5	10.0
MW-5-P15	1.5" DP	2	1.6	11.5	9.9
MW-8-C	2" "HSA"	1	1.5	11.5	10.0
MW-8-P05	0.5" DP	4	2.5	11.5	9.0
MW-8-P10	1" DP	3	1.5	11.5	10.0

MW-8-P15	1.5" DP	2	1.6	11.5	9.9
MW-9-C	2" "HSA"	1	3.4	12.9	9.5
MW-9-C-New	2" "HSA"	1	2.5	12.3	9.8
MW-9-P05	0.5" DP	4	3.8	12.8	9.0
MW-9-P10	1" DP	3	2.6	12.6	10.0
MW-9-P15	1.5" DP	2	3.0	12.9	9.9
MW-9-P15-New	1.5" DP	2	2.6	12.5	9.9
MWD-11-C	2" "HSA"	1	3.0	28.0	25.0
MWD-11-P05	0.5" DP	4	4.4	28.4	24.0
MWD-11-P10	1" DP	3	3.5	28.5	25.0
MWD-11-P15	1.5" DP	2	1.8	28.0	26.2
MWD-9-C	2" "HSA"	1	3.0	28.0	25.0
MWD-9-P05	0.5" DP	4	4.4	28.4	24.0
MWD-9-P10	1" DP	3	3.4	28.4	25.0
MWD-9-P15	1.5" DP	2	1.8	28.0	26.2
T-6-5C	2" "HSA"	1	4.0	19.0	15.0
T-6-5C-New	2" "HSA"	1	4.4	19.4	15.0
T-6-P05	0.5" DP	4	4.0	19.0	15.0
T-6-P10	1" DP	3	4.0	19.0	15.0
T-6-P15	1.5" DP	2	2.6	19.0	16.4
T-6-P15-New	1.5" DP	2	2.4	18.6	16.2

3.5.2 Period of Operation

Table 3-10 represents a Gantt chart of major milestones accomplished over the 6 year project duration. Many ancillary efforts were also conducted by project team members such as conference presentations, papers and poster boards, management of large databases and ongoing networking efforts with state and federal regulatory agencies, universities, and experts from industry and standards organizations. While not presented in Table 3-10, these efforts contributed substantially to the high degree of positive recognition from industry and regulatory professionals and successful technology transfer within and outside the DoD complex.

Table 3-10. Project Milestones.

Milestone	FY00				FY01				FY02				FY03				FY04				FY05				FY06			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Phase I Events																												
ESTCP kick-off meeting																												
Contracts awarded																												
ASTM draft standard																												
Draft Demo Plan submitted																												
Well installations completed																												
Sampling Event #1																												
Sampling Event #2																												
Final Demo Plan submitted																												
Sampling event #3																												
Sampling Event #4																												
Sampling Event #5																												

Phase II Events																												
Advisory Committee Meeting																												
Phase II white paper																												
Host ITRC SCM team meeting																												
ANOVA statistics for Phase I data																												
ITRC Tech Reg development																												
Hydraulic conductivity tests																												
New well clusters installed																												
Water Well Journal Paper																												
Sampling Event #6																												
Sampling Event #7																												
Sampling Event #8																												
Sampling Event #9																												
Sampling Event #10																												
Sampling Event #11																												

Sampling Event #12																						■						
Sampling Event #13																							■					
Phase II Statistical Analysis																								■				
Phase I&II combined ANOVA																								■	■	■		
ITRC internet training modules																								■	■	■	■	■
Draft Final Report																									■	■	■	■
ITRC Tech Reg Published																										■		
Draft C&P Repot																											■	■

3.5.3 Amount /Treatment Rate of Material to be Treated
Not Applicable.

3.5.4. Residuals Handling
All residuals resulting from well installation, development, and sampling were handled in accordance with regulatory approved methods practiced by facility hazardous waste management personnel. Prior to each waste generating event, facility waste management personnel were contacted, and a management plan was developed and implemented. Following each waste generating event, facility waste management personnel collected consolidated and labeled materials, which were incorporated into the facility waste management process for on-site treatment or off-site disposal at a certified repository.

3.5.5 Operating Parameters for the Technology
Please see Sections 3.5.6 and 3.5.7.

3.5.6 Experimental Design
The project experimental design was aimed specifically at answering key questions regarding DP wells performance relative to conventional drilled wells. These questions included the following:

- Do DP wells provide similar or comparable solute concentration information relative to conventional drilled wells?
- Do DP wells provide similar or comparable solute concentration information relative to conventional drilled wells over time periods exceeding several years?
- Do DP wells yield similar or comparable hydrogeologic information relative to conventional drilled wells?
- Will site management decisions be the same for both DP and conventional drilled well installation methods?

The project was conducted at five sites comprised of different soil types (including clay to sand), depths to groundwater (ranging from 5 feet below grade to more than 100 feet below grade), climate (ranging from Mediterranean to below freezing winters), and available infrastructure. At some sites, such as Hanscom, DP wells were installed adjacent to drilled wells installed during previous activities to form well pairs. At Port Hueneme, every well was installed specifically for this well comparison project in the form of clusters, so much more experimental design flexibility was afforded. In addition, the clusters at Port Hueneme were designed to minimize solute impact due to dispersive flux by setting well screens in zones of relatively high hydraulic conductivity. Furthermore, the Port Hueneme drilled wells, and some of the DP well representatives, were designed in accordance with ASTM D5092. Additional details are presented in Sections 3.3 and 3.5.1.

3.5.7 Sampling Plan

The sampling plan was developed based on a combination of previous site characterization efforts, the need to reduce potential biases due to extraneous items such as sampling order, and the need to conform with current industry practices. Since each site was in a different restoration phase when incorporated into a multi-site demonstration, pre-sampling events differed. For instance, for Dover, an ongoing monitoring and remediation system was in-place during the demonstration, so augmentation of the drilled monitoring well field was required. In contrast, at Port Hueneme, well clusters were initially installed within the leading edge of the known solute plume (Cell B) as well as downgradient of the plume (Cell A).

Additionally, a historical review of existing groundwater contaminant distribution and hydrogeologic data was performed, when such data was available, during the well location selection process to avoid any areas with the following characteristics: (1) high concentration gradients, (2) areas with consolidated materials (e.g., rock and gravel), (3) areas with any DNAPL or LNAPL distribution, and (4) areas with steep potentiometric surfaces. For the majority of the demonstration well locations, all criteria were met. However, based on data from field observations and historical analytical results, it is believed that DNAPL may be present adjacent to one of the clusters, and that the concentration gradient has consistently demonstrated higher values in a 1.5 inch well relative to the other wells in the Tyndall AFB cluster, possibly due to proximity to the NAPL (Section 4.3.1).

Lack of adequate suppression of any of the listed extraneous factors can lead to greater variability in the intra-well and paired differences of groundwater monitoring data obtained. Such variability diminishes the value of the statistical analyses, and thus necessitates a greater number

of independent samples to achieve the same level of *confidence* and *power* in the resulting comparison.

The objectives of this sampling program were to collect water samples from wells where the constituents of concern included volatile organic compounds. Additionally, since the study was a demonstration to support and validate the use of CPT-installed wells, and an inorganic contaminant site was not included in the demonstration, inorganic analytes were included in the comparisons to serve as proxies for sites contaminated with inorganic constituents. For all sampling, a low-stress (low-flow) purging and sampling procedure was implemented. A protocol for this technique, published in EPA/540/S-95/504, Low-Flow (Minimal Drawdown) Ground-Water Sampling Procedures (Puls and Barcelona, 1996) was strictly adhered to.

A summary of the general pre-sampling, sampling, and post-sampling logistics are presented below. Notes are included where site-specific logistics differed from the other sites in the demonstration.

Pre-Sampling. The test cell locations were checked at least one day before each sampling event. The cells were evaluated for potential obstructions (parked vehicles, stored materials, etc.) and a pallet with an empty wastewater drum was placed in an appropriate location adjacent to each cell. The field crew reviewed the field implementation plan to ensure that the types of samples, numbers of samples, and sampling randomization logistics were understood and that all field logistics were addressed accordingly. Laboratory personnel were contacted and times were established for sample courier pickup times and places. Labels for the sample bottles were printed to include the well identifier and date and time sampled. The Hydrolab™ was calibrated and the battery was charged.

The morning of the sampling event a canopy was deployed at the first sampling location to protect the samples and workers from solar exposure. A small gasoline generator (750-watt Honda) was set up approximately 75 feet [22.9m] down wind of the test cell. The traffic box covers were removed, and the sample pump and Hydrolab™ were set up. The monitoring wells included dedicated 1/4-inch [0.64cm] Teflon sample tubes in the wells. For the Port Hueneme wells, the sample tube was pulled up 1 or 2.5 feet [0.30 or 0.76m] (depending on well screen length) to position the end of the sample tube at the center of the screen interval. Sample tubing was held in place by a clothespin attached to the wellhead. The peristaltic pump was placed adjacent to the well so that the sample tube could be inserted directly into the influent end of the flexible pump tubing (*Masterflex* 6402-15, Norprene). The effluent end of the pump tubing was plumbed with 1/4-inch [0.64cm] polytubing and Norprene connectors to transport the effluent groundwater through the Hydrolab ™ flow-through cell and then into the wastewater drum. A new piece of pump tubing was used for every well sampled to avoid cross contamination.

Before pumping was initiated, the depth to groundwater was measured using a Solinst water level meter with a 1/4-inch [0.64cm] cable. The water level meter was decontaminated upon retrieval. The sampling pump was started and set at half speed (Pump Drive: Cole-Palmer, *Masterflex*; Console Drive Mod. # 7520-40; Pump Head: *Masterflex* Easy-Load Mod. # 7518-62). Once flow was established, the water was diverted into a graduated cylinder and timed for 1 minute. The flow rate was set to range between 460 to 480 milliliter per minute, since it was

easy to maintain and was close to conditions categorized as "low flow." This rate calibration procedure was performed at the beginning and end of the sampling of a test cell or workday, whichever came first. Samples were collected in random order according to the Environmental Security Technology Certification Program (ESTCP) Long-Term Monitoring Project team recommendations.

Sample Collection. The individuals assigned to the demonstration site collected all samples. The effluent from the pump was run through the Hydrolab™ flow-through cell at the established flow rate. The well was purged for a minimum of 5 minutes while simultaneously monitoring for stabilization of dissolved oxygen, specific conductance, temperature, and pH in accordance with ASTM D5463. If stabilization was not observed within 5 minutes, pumping and monitoring continued until stabilization was achieved. The field team noted that 10-minute purge times are about the average duration for reaching stability. Once stabilization occurred and readings were noted in the field logbook, the pump was turned off. The depth to groundwater was checked for water table drawdown before sampling. If the drawdown was greater than 0.5 feet [0.15m], pumping would continue at a reduced rate to allow the well to recover. For low-flow sampling, drawdown must be minimal (Puls and Barcelona, 1996). To date, drawdown has been negligible in all the wells during purging.

To initiate the sampling procedure, the polytubing was pulled from the effluent end of the pump tube. The Hydrolab™ flow-through cell has a check valve to prevent the back flow of wastewater. Initially a 1 liter geochemical parameter sample bottle was filled directly from the pump tube (at the established flow rate), then the pump speed was turned down to less than 100 ml per minute and the turbidity sample bottle filled. Turbidity was measured using a *Hach* Portable Turbidity Meter. Finally, a set of three 40-ml VOA sample bottles was filled for contaminant (e.g., MTBE, fuel compounds, or halogenated VOCs) analysis. The specific solute analytes are listed for each site in Table 3-11. After the parameters were measured and noted in the logbook, the 40-ml VOA bottles were put on ice and the old pump tube was discarded. The procedure was repeated for the next well in the sampling sequence. Trip blanks and matrix spike duplicates were transported with the samples to the lab when applicable (e.g., most organic constituent analyses were conducted in a fixed laboratory facility).

Post-Sampling. Samples were stored at $4^{o}C$ and delivered to the contract laboratory within 48 hours for analysis. Sampling tubes were tucked in their wells with caps placed on the wellheads and lids on the well boxes. The area was inspected for refuse generated by the sampling event (i.e., used paper products) and arrangements were made for the collection and proper disposal of the wastewater. Following field activities, field notes were entered into an electronic format for group review. Following receipt of laboratory analyses, analytical results were entered into an electronic format for data processing and management.

Table 3-11. Volatile Organic Analyte List.

Analyte	Sites Where Analytes Were Present
perchloroethene	Hanscom AFB, Tyndall AFB, DNTS
trichloroethene	CRREL, Hanscom AFB, Tyndall AFB, DNTS

cis-1,2-dichloroethene	CRREL, Hanscom AFB, Tyndall AFB, DNTS
trans-1,2-dichloroethene	Hanscom AFB, Tyndall AFB, DNTS
vinyl chloride	CRREL, Hanscom AFB, Tyndall AFB, DNTS
benzene	Hanscom AFB, Tyndall AFB, DNTS
toluene	Hanscom AFB, Tyndall AFB, DNTS
ethylbenzene	Hanscom AFB, Tyndall AFB, DNTS
o,m-xylene	Hanscom AFB, Tyndall AFB
p-xylene	Hanscom AFB, Tyndall AFB
1 ,4-dichlorobenzene	Hanscom AFB, Tyndall AFB
trichloroethane	Hanscom AFB
MTBE	Port Hueneme, DNTS

Analytical Logistics. For each well, several field analytical measurements were made. Geochemical parameters included dissolved oxygen, pH, specific conductance, temperature, and turbidity. General minerals and organic solute were analyzed using the laboratory methods listed in Table 3-12. Approximately 10 percent of additional samples were collected and analyzed for contaminant concentration in a third-party laboratory to assess quality control.

Table 3-12. List of Laboratory Methods.

Analytical Method	**Analyte/Parameter (units)**
8260	MTBE (ppb)
8260/5030/802	VOCs (ppb)
EPA 130.2 (modified)	Total Hardness (mg/L as $CaCO_3$)
EPA 160.1	Total Dissolved Solids (mg/L)
EPA 300.0	Chloride (mg/L)
EPA 300.0	Fluoride (mg/L)
EPA 300.0	Sulfate (mg/L)
EPA 310.1	Alkalinity to pH 4.5
EPA 310.1	Alkalinity to pH 8.3
EPA 353.2	Nitrate Nitrogen (mg/L)
SM-18 2320B	Bicarbonate (mg/L as CaCO3)
SM-18 2320B	Carbonate (mg/L as CaCO3)
SM-18 2320B	Hydroxide (mg/L as CaCO3)
SW-846 601 0B	Boron (mg/L)
SW-846 601 0B	Calcium (mg/L)
SW-846 601 0B	Iron (mg/L)
SW-846 6010B	Magnesium (mg/L)
SW-846 6010B	Manganese (mg/L)
SW-846 6010B	Potassium (mg/L)
SW-846 6010B	Sodium (mg/L)

Sample Analysis. For Phase I, chemical analysis of samples was performed on a quarterly basis at AFRL's laboratory for selected compounds using EPA SW-846 methods, including method 8260, method 5030 purge and trap for sample extraction and modified EPA method 802 1B for the analysis of volatile organic compounds in water. Phase II laboratory analyses were conducted by the Environmental Chemistry Branch of the Environmental Laboratory, Corps of Engineer's Engineer Research and Development Center (ERDC-EL). Modifications to method 802 1B included the use of a capillary column in place of a packed column and truncation of the standard analyte list. The truncated target analyte list included only the purgeable halocarbons, aromatics, and MTBE as presented in Table 3-12.

Phase I split samples for laboratory Quality Assurance/Quality Control (QA/QC) were sent to Severn-Trent Laboratories (STL, Colchester, Vermont). Phase II split samples were analyzed by CAPCO Analytical Laboratories (Ventura, California). Analyses of split samples were performed using Gas Chromatography/Mass Spectrometry (GC/MS) following EPA Method 8260.

Experimental Controls. Approximately 10 to 20 percent of additional samples were collected and analyzed for contaminant concentrations in a third party laboratory to assess quality control. Duplicate wells were also installed in selected clusters for Phase II efforts to determine whether identical well designs yield statistically identical results.

The power of the statistical tests for comparing the two well installation methods is dependent on the minimization of potential extraneous factors. An extraneous factor is anything besides the installation method that may induce variability either: (1) across independent sampling events from any one well type, or (2) between the two well types during any given sampling event. Extraneous factors of the first category include:

- Variability in sampling or analysis technique
    - Variability in groundwater flow direction, velocity, or contaminant source loading

Extraneous factors of the second type include the factors above, plus:

- Variations in well materials
- Differences in well screened interval (depth and length)
- Differences in well diameter (due to impact on flow characteristics)
- Differences in well slot size (due to impact on flow characteristics)
- Defects in existing or new well construction (e.g., leaky seals, cracked casings, etc.)
    - Study-induced differences (e.g., purge sequence effects)

Extraneous factors of the second type are suppressed by:

- Matching materials between existing and new wells
- Matching screened intervals of new (DP) wells to those of existing (auger drilled) wells as closely as practicable
- Matching well diameters and slot sizes as closely as practicable
- Orienting matched pairs along an axis of low concentration gradient (e.g., the line segment drawn between two paired wells should be parallel to the local concentration isopleths)

- Randomizing the sampling sequence (e.g., alternating between "DP first" and "auger drilled first," upgradient/downgradient, etc.)

Extraneous factors of the first type are suppressed by:

- Conducting statistical analyses on wells in pairs (e.g., Wilcoxon Matched Pairs Signed Rank test, Matched Pairs *t* test)
- Installing the new (DP) well as near as practicable to the existing (auger drilled) well with which it is paired
- Strict adherence to well installation protocols (repeatability)
- Strict adherence to sampling and analytical protocols (repeatability)
- Pre-screening existing wells (or pairs) to exclude those which show a high degree of variability across independent sampling events (i.e., non-repeatability)

In formal statistical terms, the power of a test is the probability of correctly rejecting a null hypothesis when the alternative hypothesis is true. This is equal to one minus the probability of type II error (accepting a false null hypothesis). For an ANOVA F test the power depends on the ratio of the between groups and within groups variances, the number of groups, and number of samples within each group.

After Phase I of sampling, the number of samples per group was rather small (e.g., six at Port Hueneme), leading to questions about possibly low power of the tests of the effect of different well designs. The Phase II of sampling was undertaken, in part, to improve the power of the tests by increasing the number of samples per group. Accurately estimating the power of a test is difficult because it requires good knowledge of the between groups and within groups population variances, but it is possible to get a rough idea of the improvement in power resulting from the second phase of sampling by assuming that the variance estimates from the full samples are reasonable estimates of the population variances. Following this approach, which involves holding the variances constant and only change the sample sizes, the F test of the significance of well design for the Cell B layout at Port Hueneme increased from about 0.70 after the first phase of sampling to about 0.98 after the second phase. This means that the chance of incorrectly concluding that well design was not significant dropped from about 0.30 after the first phase to about 0.02 after the second phase.

Data Quality Parameters

Split samples were collected from up to 20 percent of the total number of samples. Split samples were collected from both the CPT installed wells and the conventionally installed wells. Splits were sent to a certified laboratory for analysis by EPA Method 8260 to evaluate the analytical performance of AFRL’s laboratory and the Army Laboratory. The results from the split samples provide a measure of the precision (repeatability) of the field sampling methods and help to add validity to the results from the fixed laboratories.

Trip blanks were prepared in the fixed laboratories with the same analyte-free reagent water used in the preparation of check standards and instrument blanks. They were delivered to each of the sites packaged with the empty sample containers and subsequently returned along with the filled sample containers. Equipment blanks were prepared in the field by passing analyte-free water through all decontaminated sampling equipment in the same manner that a groundwater sample

would pass. The use of equipment blanks validated the effectiveness of equipment decontamination procedures. Sites using dedicated tubing and peristaltic pumps were exempt from taking equipment blanks.

Trip blanks and equipment blanks were handled, transported, and analyzed using identical procedures as those used for regular groundwater samples. All criteria outlined in the QAPP (Appendix A) with regards to the trip blanks and equipment blanks were met during the course of this project.

Field duplicate samples were collected for 5 percent of the total number of samples collected for the purposes of preparing Matrix Spikes (MS) and Matrix Spike Duplicates (MSD). Duplicates were collected by discharging from the same pump volume, first into the original sample container and then into the duplicate container. They were identified with the suffixes MS and MSD on the Chain-of-Custody Forms. These samples helped identify matrix effects on spiked analytes of known quantity, as well as the laboratory's precision in recognizing matrix effects. All MS and MSD criteria outlined in the QAPP were met during the course of this project (Appendix A).

Groundwater sampling was performed according to the Puls and Barcelona (1996) sampling procedure. All field procedures were documented and any deviations from the protocol were noted and later evaluated for their potential to impact data quality. No significant deviations were found to occur.

Primary analytical procedures for VOCs conformed to SW-846 Standard 802 1B. SW-846 quality control measures include procedures for:

- Receiving, log-in, and storage of field samples;
- Chain-of-custody documentation;
- Standards preparation and analysis;
- Instrument calibration; and
- Instrumentation QC

Data quality procedures outlined in the project QAPP were strictly adhered to for both sampling and analysis. These procedures included EPA standard well sampling protocols and standard analytical methods. The QAPP quality control and quality assurance measures were developed with the intent of producing appropriate and defensible data for the technology demonstration. These measures received extensive programmatic, regulatory, and peer review, and were adhered to throughout the project without exception, thus assuring that the data generated support a realistic assessment of the technology.

In addition to the internal laboratory procedures, a proportion of field samples were split and sent to a third party laboratory for quality assurance. The QA laboratory, a participant in the EPA Contract Laboratory Program (CLP), provided level 3 reporting and analyzed the samples in compliance with SW-846 method 8260, a gas chromatography/mass spectrometry method for VOCs. Quality controls similar to those of the primary lab also applied to analyses conducted by the QA laboratory.

Data Quality Indicators

A project of this magnitude is comprised of several logistical challenges, each requiring careful consideration of cause and effect relationships. In an effort to present data of high quality that could potentially impact regulations and expensive program and project management decisions, the team members and their advisors planned each demonstration component with quality control given the highest priority. This is reflected in the fact that a quality control laboratory was utilized to evaluate lead laboratory results, selected duplicate wells were installed during Phase II implementation, some test cells were designed to reduce impacts from diffusive flux, and an increase in the power of the statistic was pursued, among many other actions. While this project employed multiple data quality indicators, a few of the key methods used for determining data quality are presented below.

Accuracy is the degree of agreement of a measurement or an average of measurements with an accepted reference or "true" value, and is a measure of bias in the system. The accuracy of a measurement system is impacted by errors introduced through the sampling process, field contamination, preservation, handling, sample matrix, sample preparation, and analytical techniques.

Accuracy is evaluated by the following equation:

$$\text{Percent Recovery} = \frac{\text{A - B}}{\text{C}} \times 100$$

where:

A = concentration of analyte in a spiked sample
B = concentration of analyte in an unspiked sample
C = concentration of spike added.

For this project, accuracy was assessed and controlled by the results of the following QC samples, which contain known concentrations of specific analytes (spiked):

- Matrix spike (MS) and matrix spike duplicates (MSD)
- Laboratory control samples (LCS) and LCS duplicates (LCSD)

As these samples were analyzed, spike recoveries were calculated and compared to pre-established acceptance limits. Acceptance limits are based on previously established laboratory performance or specified by the analytical methods. The control limits reflect the minimum and maximum recoveries expected for individual measurements for an in-control system. Recoveries outside the established limits indicate error in addition to normal measurement error, and the possible need for corrective action. Corrective action may include re-calibrating the instrument, re-analyzing the QC samples, re-analyzing the sample batch, re-preparation of the sample batch, or flagging the data (if problems can not be resolved). For contaminated samples, matrix spike recoveries may be dependent upon sample homogeneity, matrix interference, and dilution requirements.

Laboratory accuracy was evaluated using the results for MS/MSD, and LCS/LCSD sample analyses. As with precision, the accuracy objectives for the data are based on laboratory established limits, and vary with the specific analyte.

Although there is no way to quantitatively measure the accuracy of the field program using percent recovery, some aspects of accuracy can be assessed, such as comparing the length of the water-level probe to another measuring tape of known length and proper calibration of the field instruments.

Precision is the reproducibility of measurements under a given set of conditions. For large data sets, precision is expressed as the variability of a group of measurements compared to their average value (i.e., standard deviation). For duplicate measurements, precision is expressed as the relative percent difference (RPD) of a data pair and is calculated using the following equation:

$$\mathrm{RPD} = \frac{[\mathrm{A - B}]}{([\mathrm{A + B}]/2)} \times 100$$

where: A and B are the reported concentrations for sample duplicate analyses.

For this project, precision was assessed by calculating the RPD of the MS/MSD sample pairs and the duplicate and replicate sample pairs and comparing the results to laboratory established RPD control limits. Precision of duplicate samples is dependent upon sample homogeneity. The data quality objectives for precision during this program were based on laboratory established control limits, which are specific to each analyte.

The analyst, group leader, or technical advisor is responsible for investigating data outside the QC limits. Corrective action may include re-calibrating the instrument, re-analyzing QC samples, re-analyzing samples, or flagging the data.

Sampling precision in the field program is affected by the procedures used for sample collection, handling, and transportation. To reduce the variability that may be introduced during sampling, Section 3.5.7 outlines the standard sampling, handling, and shipping procedures that were used for each sampling program.

Completeness is defined as the percentage of valid data relative to the total number of analytes and is evaluated using precision, accuracy, and holding time criteria. Completeness was calculated using the following equation:

$$\mathrm{Completeness} = \frac{\mathrm{Valid\ Data}}{\mathrm{TotalData}} \times 100$$

Project completeness was determined at the conclusion of the data validation and was calculated by dividing the number of valid sample results by the total number of samples analyzed. The completeness objective for this project was 90 percent for all data, as recommended in USEPA guidelines (USEPA, 1988a).

Completeness of the field program was evaluated to ensure that the appropriate numbers of samples were collected for analysis, and that field data of the type and quantity outlined in the Section 3.5.7 were collected. Completeness of the field investigations was evaluated by comparing the actual number of samples and the actual quantity of data collected to the requirements outlined in the Technical Demonstration Plan.

Method detection limits were determined in accordance with the procedures in SW-846 and 40 CFR Part 136. This procedure includes analyzing seven or more prepared spikes or standards in reagent water at levels 3 to 5 times the estimated detection limit. The standard deviation of the replicate measurements is calculated, and the MDL is computed as shown below. The MDL calculated by the procedure described above is defined as "The minimum concentration of a substance that can be measured in reagent water and reported with a 99 percent confidence that the analyte concentration is greater than zero."

$$MDL = t_{(n-1,\ 0.99)}s$$

where: $t_{(n-1,\ 0.99)}$ = Students' *t* value for a one-sided, 99 percent confidence level and a standard deviation estimate with n-1 degrees of freedom; s = standard deviation of replicate analyses of matrix spikes (reagent water).

For Gas Chromatography, initial calibration consists of determining the linear range, establishing detection limits, and establishing retention time windows. The calibration was then checked daily to ensure that the system calibration remains within specifications. If the daily calibration check did not meet established criteria, the system was re-calibrated.

Calibration standards were prepared according to the standard operating procedure for the method. For the SW-846 8000 series methods, a calibration standard was prepared for each analyte of interest at five concentration levels. One of these standards was slightly above the method detection limit. The other standards were selected to bracket the concentration range expected in the environmental samples, but not to exceed the working range of the detector.

A reagent water blank was run prior to calibration to show the absence of interferences. The calibration standards then were introduced into the system and a calibration curve generated for each analyte. The response factor for each analyte at each concentration was calculated as follows:

$$\text{Response Factor (RF)} = \frac{\text{Total Area of Peak}^{(a)}}{\text{Mass Injected (in nanograms)}}$$

[(a)] For multi-response analytes, the areas from at least five major peaks were used for quantitation.

Acceptance criteria for instrument response linearity checks were based upon the correlation coefficient (r) of the best fit line for the calibration data points, or on the percent relative standard deviation (%RSD) for response factors calculated for each analyte at each level over the working range. The correlation coefficient was calculated as:

$$r = \frac{n\sum(xy) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\left(\sum x^2\right) - \left(\sum x^2\right)\right]\left[n\left(\sum y^2\right) - \left(\sum y^2\right)\right]}}$$

where: x = calibration concentrations
y = instrument response (peak area)
n = number of calibration points (x and y data pairs).

The percent RSD is calculated as:

$$\%RSD = \frac{SD}{\bar{c}} \times 100$$

where: %RSD = relative standard deviation

$\bar{c}$ = means of 5 initial RFs for a compound

SD = standard deviation of the RFs for a compound

$$SD = s\sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left[\sum_{i=1}^{n} x_i\right]^2 / n}{n-1}}$$

If the coefficient of correlation, r, was greater than or equal to 0.995, or the %RSD was less than or equal to 20 percent, the calibration was considered valid. The use of r or %RSD is instrument specific and only one of these criteria will be used on each instrument.

The calibration curve and response factors were checked daily by injecting at least one calibration standard, usually the mid-range standard. The percent difference between initial and continuing response factors were calculated using the following equation:

$$\%\,\text{Difference} = \frac{\left(\text{RF}_1 - \text{RF}_c\right)}{\text{RF}_1} \times 100$$

where: RF_1 = average relative response factor from initial calibration

RF_2 = response factor from continuing calibration

An acceptable percent difference was within plus or minus 15 percent.

Retention time windows were established for each analyte during initial calibration per SW 846, Method 8000. The retention time window was checked prior to sample analysis using the calibration check standard. A warning limit specific to the method was used. If the standard failed to meet the retention time window, the instrument was re-calibrated.

For Gas Chromatography/Mass Spectrometry (GC/MS), each day prior to analysis of samples for VOCs, the instrument was tuned with bromofluorobenzene (BFB) (according to the tuning criteria specified in the USEPA Contract Laboratory Program [CLP]). No samples were analyzed until the instrument has met tuning criteria. After the instrument met tuning criteria, it was then calibrated for all target compounds. An initial calibration curve was produced, and certain compounds referred to as System Performance Calibration Compounds (SPCC) and Continuing Calibration Compounds (CCC) were evaluated to ensure that the system was within calibration. If the daily SPCCs and CCCs did not meet the established criteria, the system was re-calibrated. Calibration standards at a minimum of five concentrations were prepared by secondary dilution of stock standards. All or a subset of the compounds listed in EPA Methods 8260 were used as calibration standards.

Each calibration solution including internal standards and surrogates were introduced according to EPA Method 5030 for volatile compounds. A relative response factor (RF) was calculated for each compound relative to the internal standard whose retention time was closest to the compound being measured. The RF was calculated as follows:

$$RF = \frac{\left(A_x C_{is}\right)}{\left(A_{is} C_x\right)}$$

where: A_x = Area of characteristic ion for the compound being measured
A_{is} = Area of characteristic ion for the specific internal standard
C_{is} = Concentration of the specific internal standard
C_x = Concentration of the compound being measured.

The average relative response factor (RF1) was calculated for each compound using the values from the five-point calibration. A system performance check was made before the calibration was accepted as valid. The SPCCs were checked for a minimum average relative response factor. The five volatile SPCCs were chloromethane, 1,1-dichloroethane, bromoform, 1,1,2,2-tetrachloroethane, and chlorobenzene. The minimum acceptable average relative response factor for volatile compounds was 0.250).

The percent relative standard deviation (% RSD) for the CCCs were calculated from the RFs in the initial calibration and met specified criteria. The volatile CCCs were 1,1-dichloroethane, 1,2-dichloropropane, toluene, ethylbenzene, and vinyl chloride. The formula used to calculate % RSD was:

$$\% RSD = \frac{SD}{\bar{c}} \times 100 \; \% RSD = D \times 100$$

where: RSD = Relative Standard Deviation
$\bar{c}$ = Mean of 5 initial RFs for a compound
SD = Standard deviation of the RFs for a compound

$$SD = s\sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left[\sum_{i=1}^{n} x_i\right]^2 / n}{n-1}}$$

Every 12-hour shift, each GC/MS was tuned by purging or injecting 4-bromofluorobenzene (BFB) for volatile compounds. Also, initial calibration of the GC/MS was checked by analyzing a calibration standard (usually the mid level standard) and checking the SPCC and CCC performance. If the minimum relative response factors for SPCCs were not met, corrective action was taken before samples were analyzed. The percent difference of relative response factor compared to the average relative response factor from the initial calibration was calculated as follows:

$$\% \text{ Difference} = \frac{\left(\mathrm{RF}_1 - \mathrm{RF}_c\right)}{\mathrm{RF}_1} \times 100$$

where: RF_1 = Average relative response factor from initial calibration
RF_c = Relative response factor from current calibration check standard.

If the percent difference criterion for each CCC compound was met, the initial calibration was assumed to be valid. If the criterion was not met for any CCC, corrective action was taken. A new five-point calibration was generated if the source of the problem was found and corrected.

The internal standard responses and retention times in the CCC were evaluated. If any internal standard retention times changed by more than 30 seconds from the last calibration check (12 hours), the system was checked for malfunctions and corrected as necessary. If the extracted ion current profile (EICP) areas for any of the internal standards changed by a factor of two from the

last daily calibration standard check, the system was checked for malfunctions and corrections made as necessary. All samples analyzed during the time the system was malfunctioning were re-analyzed.

Calibration Procedures, Quality Control Checks, and Corrective Action
All factory instrumentation calibration procedures were followed for field and laboratory equipment. Quality control checks were implemented according to factory and laboratory established standard protocol. Corrective action was taken when analytical tolerances were not met.

3.5.8 Demobilization

All wells installed and utilized for this demonstration will eventually be decommissioned and removed. As of the writing of this report, many of the wells and associated infrastructure (e.g., storage lockers, field equipment, sampling tubes, fencing, etc.) remain in place. For at least the Port Hueneme site, all wells have been removed. Plans and funding are in place to decommission and remove all remaining wells and auxiliary equipment.

3.6 Selection of Analytical/Testing Methods

The analytical methods used for monitoring volatile organic compounds (VOC) were selected based on feedback from the regulatory community, with specific consideration given to long-term regulatory monitoring. Standards described in EPA SW-846 (USEPA, 1996) were identified as the most appropriate analytical methods for evaluating VOCs in groundwater for this study. Calibrated field monitoring devices, as described in the sampling protocol and QAPP, were used to analyze water quality parameters monitored during pre-sampling well purging.   Methods for evaluating inorganic species were selected to match the parameter list developed by NAVFAC ESC on a previous project.

Where appropriate, well installation methods were based on ASTM standards (e.g., ASTM D5092 for well design). For situations where these did not exist, team members participated in the development of new standards (e.g., ASTM 6724 and D6725).

3.7 Selection of Analytical/Testing Laboratory

Air Force Research Laboratory, Air Expeditionary Forces Technologies Division, Weapons Systems Logistics Branch (AFRL/MLQL), located at Tyndall AFB, Florida, served as the primary analytical laboratory for performing analyses of the groundwater samples collected during Phase I of this project. Severn-Trent Laboratories (STL), located in Colchester, Vermont, provided quality assurance sample analytical services. Laboratory selection criteria consisted of participation in the EPA Contract Laboratory Program, prior reputation with the project team, and cost. Lancaster Laboratory (Lancaster, Pennsylvania) was selected as the as the analytical lab for the Phase I inorganic analyses under subcontract to NAVFAC ESC via Bechtel government services.

Phase II contaminant laboratory efforts were conducted by the Army Environmental Chemistry Branch of the Environmental Laboratory, Corps of Engineer's Engineer Research and Development Center (ERDC). CAPCO Analytical Laboratory in Ventura, California analyzed Inorganics. The Army lab was selected based on their reputation and working relationship with

several team members. CAPCO was selected for their reputation based on contracting logistics and requirements.

4.0 PERFORMANCE ASSESSMENT

4.1 Performance Criteria

Table 4-1. Performance Criteria Description, Primary or Secondary.

Performance Criteria	Description	Primary or Secondary	Success Criteria
Factors Affecting Technology Performance	How well design impacts observed chemical and hydrological results	Primary	No difference compared to control
Versatility	Potential for use in applications other than LTM	Secondary	No difference compared to control
Hazardous Materials	Potential for use at various types of contaminant sites	Primary	No difference compared to control
Process Waste	Whether waste stream volumes are less or more than HSA	Secondary	Less waste compared to control
Reliability	Potential breakdowns of the equipment, sensitivity to environmental conditions	Secondary	No difference compared to control
Ease of Use	Number of people required, level of skill required, installation time requirements, monitoring requirements	Primary	No difference or lower labor and time requirements compared to control
Long-Term Performance	Whether representative data can be collected for LTM applications	Primary	No difference compared to control

4.2 Performance Confirmation Methods

Performance criteria, metrics, and confirmation methods are presented in Table 4-2. Quantitative criteria included technology performance, hazardous materials, ease of use, and long-term performance. Qualitative criteria included versatility, process waste generation, and technology reliability. Sampling, field and laboratory measurements, field experience, and associated statistical methods were used to confirm whether or not the expected performance metrics were met.

Table 4-2. Expected Performance and Performance Confirmation Methods.

Performance Criteria	**Expected Performance Metric**	**Confirmation Methods**
Primary Criteria (Performance Objectives – Quantitative)		
Technology Performance	Statistically comparable chemical and hydraulic measurements; less than 10 percent of total observable error due to well design differences	Statistical comparison of chemical and hydraulic measurements
Hazardous Materials	Statistically comparable chemical concentrations at various contaminant release sites; less than 10 percent of total observable error due to well design differences	Statistical comparison of chemical measurements
Ease of Use	Comparable or lower labor and time requirements for DP wells	Documented experience from field demonstration
Long-Term Performance	Statistically comparable chemical measurements; less than 10 percent of total observable error due to well design differences	Statistical comparison of chemical measurements
Secondary Criteria (Performance Objectives – Qualitative)		
Versatility	Comparable chemical and hydraulic measurements	Documented experience from field demonstration
Process Waste	Comparable or less waste volume than HSA installations	Documented experience from field demonstration
Reliability	Comparable equipment reliability and sensitivity to environmental conditions	Documented experience from field demonstration

Data quality procedures outlined in the project QAPP were strictly adhered to for both sampling and analysis. These procedures included EPA standard well sampling protocols and standard analytical methods.

Groundwater sampling was performed according to the most commonly applied low-stress sampling procedure (Puls and Barcelona, 1995). All field procedures were documented and any deviations from the protocol were noted and later evaluated for their potential impact on data quality. No significant deviations were found to occur.

Primary analytical procedures for VOAs conformed to SW-846 Standard 802 1B. Quality controls on this standard included procedures for:

- Receiving, log-in, and storage of field samples;
- Chain-of-custody documentation;
- Standards preparation and analysis;
- Instrument calibration; and
- Instrumentation QC

These quality control and quality assurance measures were developed with the intent of producing appropriate and defensible data for technology evaluation and demonstration. They received extensive programmatic, regulatory, and peer review, and were adhered to throughout the project without exception, thus assuring that the data generated support a realistic assessment of the technology.

In addition to the internal laboratory procedures, a proportion of field samples were split and sent to a second laboratory for quality assurance. The QA laboratory, a participant in the EPA Contract Laboratory Program (CLP), provided level 3 reporting and analyzed the samples in compliance with SW-846 method 8260, a gas chromatography/mass spectrometry method for VOAs. Quality controls similar to those of the primary lab also applied to analyses conducted by the QA laboratory.

Statistical tests of hypothesis were used to compare the performance of DP wells to that of HSA wells for groundwater monitoring. These tests were thoroughly described in section 4.5.1 of the project workplan, and are summarized below.

4.3 Data Analysis, Interpretation and Evaluation

4.3.1 Analytical Data

Statistical analyses were conducted on the purge parameter data and on the concentrations of inorganic analytes and organic contaminants. Statistical analyses were used to determine whether there was a significant difference between the results from any of the DP wells versus those from the conventional HSA wells. Data for each test site and each analyte (or parameter) were analyzed separately. Whenever possible, standard parametric tests were used on normally distributed sets of raw data where the variances were homogeneous or, on the log-transformed data, if it was normally distributed and the variances were homogeneous. In instances where a parametric test could not be used, a non-parametric test was used.

Specifically, for the sites with pairs of wells (e.g., Dover AFB and Hanscom AFB), a Paired *t*-test was used if the data (or log data) were normally distributed and the variances were homogeneous. In instances where these requirements were not met, a Wilcoxon Signed Rank test was used.

At the remaining test sites, a one-way Repeated Measures Analysis of Variance (RM-ANOVA) test was used on any normally distributed data (either raw or log-transformed data). Where significant differences were found between the well types, a Holm-Sidak Multiple Comparison test was used to determine which wells were significantly different. In instances where the parametric test was not appropriate, a Friedman Repeated Measures Analysis of Variance on Ranks was used. In instances where a significant difference was found, a Tukey Multiple Pairwise Comparison test was used to determine which wells were significantly different from each other.

Whenever adequate data was available, two-way RM-ANOVA tests were used to determine the significance of well location and well type and to determine whether there was a significant interaction between well type and well location. A significant interaction indicates that there is no consistent trend that can be associated with well type. However, this type of test requires that there not be any missing values in the data set. In instances where there were missing values, the data set had to be edited so that the matrix was complete, i.e., there were no missing values. This typically means that the analyses are conducted on a smaller data set than what was used for the one-way RM-ANOVA tests.

Additional ANOVAs tests were conducted on the Port Hueneme data from Phase I. These analyses were used to test the effect of well type, well location, well depth, and sampling date and allowed the researchers to determine the effect of spatial heterogeneity and temporal affects on these data.

For all the data, in instances where the concentration was reported to be below the detection limit, half the detection limit was used to estimate of the concentration. Entries with "J" values were used to denote sample results where a measurable concentration was obtained but the concentration was below the detection limit.

Because the presence of large numbers of non-detects skews the statistical analyses, only sampling dates where the majority of wells (50 percent or more) had detectable concentrations were included in a data set. Therefore for two-well comparisons, at least one of the wells had to have a measurable concentration for that sampling date to be included in the data set. For three-well and four-well comparisons, there had to be at least two wells with measurable concentrations. For five-well and six-well comparisons, there had to be at least three wells with measurable concentrations. For seven-well comparisons, there had to be at least four wells with measurable concentrations. Similar rules were used if there were missing values. Generally, only data sets where there were at least six sampling events with useable data were used for the statistical analyses.

In addition, an alternative statistical approach that allowed for including non-detect information was used in cases where there were substantial numbers of non-detects. Concentration data were

converted into binary detect/non-detect records, and Pearson's Chi-square tests of independence were employed to test the probabilities of obtaining the same outcome (detect or non-detect) in paired control and test wells. If wells are responding in similarly in situations where concentrations are low, then the frequencies of matching results should be substantially higher than would be expected by chance. The results of these statistical analyses are important in assuring that the same management decision would be made when analyte concentrations are near the detection limit.

CRREL Results:

For Phase I, three pairs of wells were to be evaluated. Each pair consisted of a 4-inch diameter HSA well with a 10-foot screen and a conventional filter pack, and a ½-inch diameter DP well with a 9-foot screen and a Geoprobe pre-pack filter pack. The top of the screened interval in these wells ranged from 106.5 to 126.5 feet below the ground surface. However, none of the ½-inch DP wells could be sampled during Phase I because of problems related to the small-diameter of the bladder pump and the amount of lift required to raise the groundwater 100 feet (or more) to the surface.

Since no samples were recovered from the ½-inch DP wells during Phase I, installation of ¾-inch DP wells was considered for Phase II. At that time, three different brands of ¾-inch diameter bladder pumps were commercially available, and it seemed reasonable to assume that at least one could successfully allow for sample recovery. In contrast, there was only one manufacturer of a ½-inch bladder pump at the time this additional well representative was contemplated. After testing two of the commercially available ¾-inch diameter bladder pumps in our conventional wells and finding that both delivered water to the surface, the investigators installed a ¾-inch DP well adjacent to each of the three well pairs. These DP wells were constructed with a 10-foot screen and a Geoprobe pre-pack filter pack. The resulting three well clusters each contained three distinct well types.

Shortly after installing the ¾-inch DP wells, the manufacturer of the ½-inch bladder pump redesigned the pump, and this allowed two of the three ½-inch DP wells to be sampled. Unfortunately, the deepest ½-inch well (Cluster 9) still did not yield samples.

Since samples were not recovered from one of the ½-inch DP wells (Cluster 9), two separate sets of statistical analyses were conducted. One set of analyses compared the three well types at two well clusters (Clusters 10 and 11); while the other set of analyses compared the ¾-inch DP wells with the conventional wells at the three well clusters.

<u>Field parameter data</u>

Table 4-3 presents the mean data for field parameters, which included turbidity, temperature, salinity, specific conductance, and DO. There were no statistically significant differences between the values for the DP wells and the conventional wells for temperature, but statistically significant differences were observed for the remaining parameters. Turbidity values and DO levels were statistically significantly higher in both DP well types than in the conventional wells, and specific conductance and salinity values were statistically significantly higher in the ¾-inch DP wells (Table 4-4). However, with the exception of specific conductance, these differences were generally quite small in magnitude.

Table 4-5 presents the mean values for the specific conductance for the three well types comprising well Clusters 10 and 11. There was a relatively large difference between the mean values for the ¾-inch well vs. the conventional well at Cluster 11 but not at Cluster 10. Statistical analyses of the data for each cluster conducted separately revealed that this difference was statistically significant at Cluster 11 but not at Cluster 10.

Table 4-3. Mean values for field parameters at CRREL.

		Mean values for clusters 10 & 11		
Parameter	**Units**	**4-in. HSA**	**3/4-in. DP**	**1/2-in. DP**
DO	mg/L	5.1	**5.8***	**8.9***
Salinity	ppt	0.2	**0.3***	0.2
Specific Conductance	µS	430	**677***	427
Temperature	°C	13.9	14.5	15.2
Turbidity	NTU	0.8	**2.8***	**2.1***

* Values statistically significantly different than values from conventional HSA well.

Table 4-4. Results of statistical analyses of CRREL field parameter data.

						Sig. dif. w/ HSA well?	
Parameter	**Wells compared**	**Sig. Dif.?**	**Type of test**	**Prob.**	**Power**	**1/2-in DP**	**3/4-in DP**
- **Turbidity**	3/4" DP & 4" HS	**Yes**	Wilcoxon Signed rank	0.028	-		**Yes**
	all three types	**Yes**	Friedman RM ANOVA on ranks	0.009		No	**Yes**
Temperature	3/4" DP & 4" HS	No	Paired t-test	0.848	0.05		No
	all three types	No	RM ANOVA on raw data			No	No
Salinity	3/4" DP & 4" HS	**Yes**	Wilcoxon Signed rank	0.004	-		**Yes**
	all three types	No	Friedman RM ANOVA on ranks	0.531		No	No
Spec. Conduct.	3/4" DP & 4" HS	**Yes**	Wilcoxon Signed rank	0.046			**Yes**
	all three types	**No**	Friedman RM ANOVA on ranks	0.005		**No**	**No**
DO	3/4" DP & 4" HS	Yes	Wilcoxon Signed rank	0.006			**Yes**
	all three types	Yes	Friedman RM ANOVA on ranks	<0.001		**Yes**	No

Table 4-5. Mean Specific conductance for CRREL well clusters.

	Mean Specific Conductance (µS)		
	4-in. HS	¾-in. DP	½-in. DP
Mean cluster 10	495	460	**402***
Mean cluster 11	356	**920***	456
Mean 10 & 11	430	**677***	427

* Values statistically significantly different than values from conventional HSA well.

<u>Inorganic analytes</u>

During most of Phase II, metals analyses were limited to primarily metals that might leach from the stainless steel components of the wells and sampling pumps. Specifically, the metals analyzed included: barium, cadmium, chromium, copper, iron, lead, manganese, molybdenum, and nickel. Only two analytes, barium and chromium, were found at detectable concentrations that allowed for statistical analyses (Table 4-6). Examination of the mean data reveals that in some instances there was good agreement between the mean values while in other cases the agreement was not as good. However, there does not appear to be a consistent trend associated with the mean values for either well type (i.e., one type of well always has higher concentrations). Statistical analyses of the data set containing all three well clusters revealed that there were no statistically significant differences between the concentrations in the DP wells and the conventional wells for either analyte (Table 4-7). There also were no statistically significant differences between the ½-inch DP wells and the conventional wells for either barium or chromium. Thus, there is no consistent bias associated with either well type.

For the other metal analytes, concentrations were generally below the detection limit. This indicates that metal constituents did not leach from the stainless steel screens on the pre-pack filters.

Table 4-6. Mean concentrations of detectable metals in CRREL wells.

		Mean conc. (µg/L)	
Analyte	Cluster #	4-in. HSA	3/4-in. DP
Barium	9	164	65
	10	32	34
	11	21	64
Chromium	9	49	18
	10	2.5	2.8
	11	6.2	5.5

Table 4-7. Summary of statistical analyses of the CRREL inorganic and organic data.

Analyte	Wells compared	N	Sig. Dif.?	Type of test	Probability	Power
Barium	3/4-in. DP & HS	12	No	Paired t-test on logs	0.97	
	All 3 wells	5	No	Friedman RM-ANOVA on ranks		
Chromium	3/4-in. DP & HS	12	No	Paired t-test on logs	0.194	0.133
	All 3 wells	6	No	RM-ANOVA on logs	0.526	0.049
TCE	3/4-in. DP & HS	17	**Yes**	Wilcoxon signed rank	0.034	
		22		2-way RM-ANOVA		
			Yes	location	<0.001	
			Yes	well type	0.003	
			Yes	interaction	<0.001	

Organic contaminant, TCE

TCE was the only contaminant known to have been released at this site, and the only contaminant found in measurable concentrations in all the wells. Table 4-8 presents the mean concentration of TCE for each of the well types and locations. Statistical analyses indicated that there was a statistically significant difference between the ¾-inch-diameter DP wells and the conventional HSA wells (Table 4-7). However, a two-way RM-ANOVA test revealed that the interaction between location and well type was statistically significant. This means that any differences between the well types varied with location, and more importantly, no consistent trend could be associated with well type.

Examination of the data for the mean concentrations demonstrates why this interaction was statistically significant; i.e., the mean concentrations agreed well between the DP wells and the conventional wells in Clusters 9 and 10, but this was not true for the ¾-inch DP well at Cluster 11 (Table 4-8). This difference may have been the result of natural heterogeneity at the site. However, because the magnitude of this difference was so large, the depths of the pump inlets at Site 11 were re-evaluated. The depth of the pump in the ¾-inch DP well was found to be approximately 1.5 feet higher than the pump inlet in the conventional well. This finding may explain why there were differences in the TCE concentrations and specific conductance values in this well. However, again, there were no consistent differences found that could be associated with well type for this analyte.

Table 4-8. Mean concentrations of TCE in CRREL wells.

	Mean Concentration TCE µg/L		
Location	**4-in. HSA**	**¾-in. DP**	**½-in. DP**
9	34500	33200	N/A
10	119	255	124
11	3690	15800	2120

<u>Conclusions for the CRREL site</u>
Generally, there was good agreement between concentrations in samples taken from DP wells and those taken from conventional wells at CRREL. The exception to this would be that there were statistically significant differences in TCE concentrations and Specific Conductance readings in samples taken from the ¾-inch DP well at Cluster 11. However, statistical analyses of all the data for each parameter (field parameters, metals concentrations, and TCE concentrations) indicated that there was not any consistent bias that could be associated with either the ½-inch or ¾-inch DP well construction when compared with conventionally installed monitoring wells.

DNTS Results:
For Phase I, there were six pairs of wells; each pair consisted of a 2-inch diameter HSA well with a conventional filter pack and ~10-foot screen, and a 2-inch diameter DP well with a 10-foot screen with no pre-pack filter pack. In Phase II, three additional wells were installed at two of the well pairs, generating two clusters of five wells. The additional wells consisted of a replicate 2-inch diameter HSA well, a ¾-inch DP well with a pre-pack filter pack, and a ¾-inch DP well with no pre-pack filter pack. In addition, the 2-inch diameter DP well at location 235 was replaced.

<u>Field parameter data</u>
Table 4-9 presents the mean data for field parameters and summarizes the findings from the statistical analyses for the two well comparisons (Table 4-10). For five of the six purge parameters measured in the field there were no statistically significant differences. There was a statistically significant difference for alkalinity but the magnitude of this difference was very small and most likely would not have impacted any management decision.

Table 4-9. Mean values for DNTS field parameters.

Parameter	**2-in. DP**	**2-in. HS**
Alkalinity (mg/L as Ca CO_3)	**5.6***	5.8
DO (mg/L)	3.3	3.5
ORP (mV)	268	221
Specific Conductance (µS/cm)	622	526
Temperature (°C)	16.3	16.5

Turbidity (NTU)	19	14

* Values where a statistically significant difference was found with values in conventional well.

Table 4-10. Summary of statistical analyses of 2-well data for field parameters at DNTS.

Parameter	N	Sig. Dif.?	Type of test	Prob.	Power	Mean value 2-in DP	Mean value 2-in HS
Alkalinity	82	Yes	Wilcoxon Signed Rank	0.012		5.56	5.79
DO	52	No	Wilcoxon Signed Rank	0.48		3.3	3.5
ORP	68	No	Wilcoxon Signed Rank	0.182		277	253
Specific Conductance	82	No	Wilcoxon Signed Rank	0.225		622	526
Specific Conductance*	48	No	Wilcoxon Signed Rank	0.052		311	291
Temperature	82	No	Wilcoxon Signed Rank	0.547		16.3	16.5
Turbidity	82	No	Paired t-test on logs	0.057	0.356	19	14

*Minus data with calibration issues

In contrast, there was a substantial difference between the mean values for Specific Conductance. However, statistical analyses of this data revealed that there was no statistically significant difference between these values. Table 4-11 provides the mean values for Specific Conductance for each well pair. Although there were large differences in magnitude between the well types, the well with the higher values varied from location to location (which explains why there was no statistically significant difference). Examination of the raw data revealed that these differences were due to some change that occurred in March 2004. After this date, one well suddenly exhibited values that ranged from 1,100 to 2,800, where previous values ranged from 100 to 700. The affected well (i.e., DP versus HSA) varied from location to location. Research into the cause for this change revealed that a second field probe (i.e., a used Sonde) had been acquired and was used to measure these parameters. Further examination revealed that the affected wells were always the wells where the second probe was used. After using this probe the first time, it was determined that it was out of calibration and was returned to the manufacturer for re-calibration. However, even after its return, this probe continued to yield very high values and it is questionable whether it was properly recalibrated. When the questionable data was removed from the data set, statistical analyses of the remaining data revealed that there was no significant difference between the two well types for Specific Conductance. However, even if these differences in Specific Conductance were real, there clearly was no systematic bias associated with well type.

Table 4-11. Mean values for Specific Conductance for DNTS well clusters.

	Mean value (µS/cm)	
Cluster #	**2" DP**	**2" HS**
53	453	823
235	927	254
236	729	391
237	358	752
337	962	223
354	240	775

When the newly installed Phase II DP wells were compared with the conventional monitoring wells, statistically significant differences were found in a few instances (Tables 4-12 and 4-13). For one, there was a statistically significant difference between the Specific Conductance values for some of the DP wells relative to the conventional 2-inch HSA wells. However, there also was a statistically significant difference between the new HSA wells and previously installed HSA wells. This finding supports the theory that these readings were affected by differences in the calibration of the two instruments.

Table 4-12. Mean concentrations of field parameters for 5-well comparisons at DNTS.

	Mean concentrations				
Parameter	**2-in DP no filter**	***Older* 2-in HS**	***New* 2-in HS**	**¾-in DP w/ filter**	**¾-in DP no filter**
Alkalinity (mg/L as $CaCO_3$)	**5.1**[a,b]	5.9	5.9	5.9	6.0
DO (mg/L)	2.7	2.8	2.0	**3.4**[b]	**4.7**[a,b]
ORP (mV)	307	288	282	265	**229**[a,b]
Specific Conductance (µS/cm)	**1150**[a]	400	**1070**[a]	535	**965**[a]
Temperature (°C)	18.2	16.7	17.5	17.7	18.9
Turbidity (NTU)	23	9.2	22	**28**[a]	**187**[a,b]

[a] Values were statistically significantly different from the original 2-inch HSA well.

[b] Values were statistically significantly different from the new 2-inch HSA well.

Table 4-13. Summary of statistical analyses of 5-well data for field parameters at DNTS.

Parameter	N	Sig. Dif.?	Type of test	Prob.	Power	Sig. diff w./ 2-in HS?				Sig. dif. w/ new 2-in HS?		
						2-in. DP	*New* 2-in. HS	3/4-in. DP w/ filter	3/4-in. DP No filter	2-in. DP	3/4-in. DP w/ filter	3/4-in. DP No filter
Alkalinity	20	Yes	RM-ANOVA on raw data	<0.001	0.995	Yes	No	No	No	Yes	No	No
DO	20	Yes	Friedman RM-ANOVA[1]	<0.001		No	No	No	Yes	No	Yes	Yes
ORP	12	Yes	Friedman RM-ANOVA[1]	0.009		No	No	No	Yes	No	No	No
Spec. Cond.	20	Yes	RM-ANOVA on raw data	<0.001	0.995	Yes	Yes	No	Yes	No	No	No
Temp.	20	No	RM-ANOVA on raw data	0.429	0.049	No for all						
Turbidity	20	Yes	RM-ANOVA on log data	<0.001	0.991	No	No	Yes	Yes	No	No	Yes

[1] On ranked data

For the other field parameters, there was no significant difference between the values in the new (replicate) relative to the original HSA wells. However, there were four field parameters where there was a statistically significant difference between the values reported for the ¾-inch DP wells (with no filter pack) relative to the conventional HSA wells (the new replicate and original). The mean field parameter with the largest difference in magnitude was turbidity. The high mean turbidity value for the ¾-inch DP well was mainly due to the very high values at Cluster 236. The high turbidities reported for some of these wells resulted when the wells were purged to dryness.

Inorganic analytes

During Phase I, the fifteen inorganic parameters measured at this site included: alkalinity (to pH 4.5), barium, boron, calcium, chloride, iron, magnesium, manganese, nitrate, potassium, sodium, sulfate, total dissolved solids (TDS), total hardness, and zinc. During most of Phase II, inorganic analyses were limited to metal constituents that might leach from stainless steel (although, only one of the five well types contained a stainless steel component [mesh for the pre-pack filter]). The metals that were analyzed for included: barium, cadmium, chromium, copper, iron, lead, manganese, molybdenum, and nickel. Table 4-14 gives the mean values for each well type for each of the analytes that were at measurable concentrations. Concentrations of cadmium, chromium, copper, lead, molybdenum, and nickel were generally below the detection limit.

Table 4-14. Mean concentration of inorganics in DNTS wells.

	Mean value (mg/L unless noted otherwise)	
	DP	HS
TDS	172	162
Hardness	64	58
Alkalinity	50	48
Barium (µg/L)	159	82
Boron (µg/L)	56	46
Calcium	11	12
Chloride	**25***	18
Iron	7.6	7.7
Magnesium	**8.8***	6.8
Manganese	1.7	0.8
Nitrate	1.4	1.4
Potassium	2.8	4.2
Sodium	**13***	11
Sulfate	15	12
Zinc (µg/L)	13	67

Statistical analyses revealed that there were no statistically significant differences between the two well types for the majority (12/15) of the inorganic analytes (Table 4-15). There were statistically significant differences between the two well types for chloride, magnesium, and sodium. However, these differences were not large in magnitude and most likely would not have impacted any management decision. In contrast, although there was not a statistically significant difference between the two well types for barium, there was a relatively large difference between the mean values. Examination of the raw data for the two locations revealed that this difference was due to large differences at Cluster 236. The same was true for zinc.

Table 4-15. Summary of statistical analyses of 2-well data for DNTS inorganic data.

Analyte	N	Sign. Dif.?	Type of test	Prob.	Power
TDS	24	No	Paired t-test	0.247	0.089
Total Hardness	24	No	Paired t-test on logs	0.436	0.05
Alk. to pH 4.5	24	No	Wilcoxon signed rank	0.597	
Barium	7	No	Paired t-test	0.090	0.307
Boron	14	No	Paired t-test	0.088	0.289
Calcium	24	No	Wilcoxon signed rank	0.775	
Chloride	24	**Yes**	Wilcoxon signed rank	0.008	
Iron	26	No	Wilcoxon signed rank	0.461	
Magnesium	24	**Yes**	Paired t-test on logs	0.009	0.726
Manganese	30	No	Wilcoxon signed rank	0.241	
Nitrate	13	No	Wilcoxon signed rank	0.519	
Potassium	24	No	Wilcoxon signed rank	0.749	
Sodium	24	Yes	Wilcoxon signed rank	0.031	
Sulfate	24	No	Paired t-test	0.154	0.169
Zinc	6	No	Paired t-test on logs	0.199	0.141

For three of the analytes (barium, iron, and manganese), we were able to conduct statistical analyses comparing the five well types installed for Phase II. In all cases, the data sets contained a relatively small number of comparisons, so any results from the statistical analyses should be interpreted with caution. For iron and barium, there were no statistically significant differences between the concentrations in the new replicate HSA well relative to the original HSA well, and no statistically significant differences between the concentrations in any of the DP wells and the HSA wells (Tables 4-16 and 4-17). However for manganese, there was a statistically significant difference between the concentrations in the newly installed HSA wells relative to the original HSA wells and between the ¾-inch DP (with no filter pack) relative to the original HSA well. The difference between the two conventionally installed HSA wells indicates that there was substantial spatial heterogeneity for this analyte. It is interesting that these differences appear to reflect the differences that were observed in the Specific Conductance values.

Table 4-16. Mean concentrations (μg/L) for 5-well comparison for DNTS inorganic analytes.

	2-in. DP- no-pack	2-in. HS	2-in. HS New	¾-in. DP	¾-in. DP- no-pack
Barium	159	82	100	90	330[1]
Iron	0.06	2.4	18[2]	3.0	117[2]
Manganese	0.17	0.064	**0.34***	0.059	**0.32***

[1]High due to the presence of one value that appears to be an outlier.

[2]High due to high values in Cluster 236.

Table 4-17. Summary of statistical analyses of 5-well data for inorganics at DNTS.

Analyte	N	Sign. Dif.?	Type of test	Prob.	Power*	Sig. dif. w/ 2-in HS?				Sig. dif. w/ new 2-in HS?		
						2-in. DP	*New* 2-in HS	3/4-in. DP w/ filter	3/4-in. DP No filter	2-in. DP	3/4-in. DP w/ filter	3/4-in. DP No filter
Barium	7	**Yes**	1-way RM_ANOVA on logs	0.034	0.531	No	No	No	No	No	No	No
Iron	9	**Yes**	Friedman RM-ANOVA	0.005		No	No	No	No	No	No	No
Manganese	9	**Yes**	1-way RM_ANOVA on logs	<0.001	0.953	No	**Yes**	No	**Yes**	No	**Yes**	No

Organic Contaminants

Table 4-18 gives the mean and median values for the analytes found in the 2-inch diameter HSA and DP wells. Generally, there appears to be good agreement between the mean values, and paired tests (*t*-tests or Wilcoxon Signed Rank tests) indicated that there was no statistically significant difference for the majority (10 out of 14) of the analytes (Table 4-19). There were statistically significant differences between the 2-inch-diameter HSA and DP wells (with no filter pack) for *cis*-1,2-dichloroethylene, ethylbenzene, tetrachloroethylene (PCE), and 1,1,1-trichloroethane. However, two-way RM-ANOVA tests conducted to determine the significance of well location, well type, and their interaction revealed that the interaction of well type and well location was highly statistically significant and that well type was not statistically significant after taking well location into consideration. This is shown for cDCE in Table 4-20.

Table 4-18. Mean and median organic concentrations in the wells at DNTS.

	Mean (µg/L)	**Conc.**	**Median (µg/L)**	**Conc.**
Analyte	**DP**	**HS**	**DP**	**HS**
Benzene	45	44	8	20
cis*-1,2-Dichloroethylene	**3300**	**853**	**250**	**290**
trans-1,2-Dichloroethylene	48	26		
p-Dichlorobenzene	22	16	8.9	4.4
Ethylbenzene*	**52**	**28**	**30**	**18**
MTBE	34	39	34	42
PCE*	**264**	**89**	**85**	**20**
Toluene	33	20	8.7	3.5
1,1,1-Trichloroethane*	**7535**	**493**	**68**	**60**
1,1,2-Trichloroethane	83	33	22	20
TCE	810	841	708	257
Vinyl chloride	114	53	17	10
m,p-Xylene	29	20	17	10
o-Xylene	20.8	9.3		

*Analytes where a statistically significant difference was found between the well types.

Table 4-19. Summary of statistical analyses for 2-well data for organics at DNTS.

Analyte	48	No	Wilcoxon signed rank	0.413	
Benzene	56	**Yes**	Wilcoxon signed rank	0.015	
cis-1,2-DCE	28	**Yes**	Wilcoxon signed rank	0.004	
Ethylbenzene	16	No	Wilcoxon signed rank	0.135	
MTBE	20	No	Paired t-test on log data	0.092	0.271
o-XYL	47	**Yes**	Wilcoxon signed rank	0.023	
PCE	29	No	Wilcoxon signed rank	0.971	
p-DCB	34	**Yes**	Wilcoxon signed rank	0.007	
1,1,1-TCA	16	No	Wilcoxon signed rank	1.00	
1,1,2-TCA	59	No	Wilcoxon signed rank	0.375	
TCE	24	No	Paired t-test on log data	0.108	0.236
trans-1,2-DCE	32	No	Wilcoxon signed rank	0.064	

Toluene	59	No	Wilcoxon signed rank	0.375
Vinyl chloride	48	No	Wilcoxon signed rank	0.413

Table 4-20. Mean concentrations of *cis*-1,2-dichloroethylene (µg/L) at DNTS.

Cluster #	2" DP	2" HS
53	12	3
235	122	172
236	8024	2523
237	5889	463

Analyses of the data from the two clusters of five wells also revealed that there were no significant differences between the concentrations in the new HSA wells relative to the original HSA wells and that there were no significant differences between the new ¾-inch-diameter DP wells and the HSA wells (Table 4-21).

Table 4-21. Summary of statistical analyses of 5-well data for organics at DNTS.

				Sign. dif. w/ 2-in. HS?				Sig. dif. w/ new 2-in. HS well?		
Analyte	**N**	**Type of test**	**Sig. Dif.?**	**New 2-in. HS**	**2-in. DP No filter**	**3/4-in. DP**	**3/4-in. DP No filter**	**2-in. DP No filter**	**3/4-in. DP**	**3/4-in. DP No filter**
Benzene	8	Friedman RM-ANOVA	**Yes**	No	**Yes**	No	No	No	No	No
cis-1,2-DCE	16	Friedman RM-ANOVA	**Yes**	No	**Yes**	No	No	No	No	No
PCE	14	Friedman RM-ANOVA	**Yes**	No	**Yes**	No	No	**Yes**	No	No
TCE	16	RM-ANOVA on raw data	**Yes**	No	**Yes**	No	No	**Yes**	No	No
Vinyl chloride	11	RM-ANOVA on raw data	**Yes**	No	**Yes**	No	No	**Yes**	No	No

Pearson's Chi-square tests were also conducted on the VOC data to determine the agreement between paired control (HSA) and test (DP) wells at concentrations near the detection limit (i.e., agreement between detect and non-detect data for paired wells). The results of these analyses are presented in Table 4-22. For each analyte, the table presents: the number of sample pairs (i.e., measurements taken on the same date for a well pair); the number of detects in the control well samples; the number of mismatches when there was a detect recorded in the control well and a

non-detect in the test well and vice versa; the statistical results of Pearson's Chi-square tests which test the null hypothesis that the binary responses (detect/non-detect) in the two well designs are independent (i.e., unrelated). A high probability value (P value) indicates that the null hypothesis is true and there is poor agreement between the responses for the two well types; a low P value indicates that there is good agreement.

To determine the full layout of each 2 by 2 contingency table, proceed as follows. Taking the first row as an example, 30 out of 74 samples from the control HSA wells show detects. Of these, 3 samples reveal non-detection in the test wells, while 27 exhibit concentrations above detection levels. Of the 44 samples from the control wells that are below detection (e.g., non-detect), 2 show detects in the test DP wells, while 42 resulted in non-detects. Thus the full 2 by 2 table is:

	Test Detect	**Test Non-Detect**
Control Detect	27	3
Control Non-Detect	2	42

For all the analytes except for o-xylene, the reported P values were very low (0.001 or less) thereby indicating that the null hypotheses is false and that there is good agreement between the data for the two well types. For o-xylene, although there were considerably fewer sample pairs than there were for the other analytes, the null hypothesis was also false, although the P value was not as low. Averaged over all compounds, the combined total of the two types of mismatches is about 11.7 percent, so paired control and test wells give the same outcome in 88.3 percent of the samples. This is much higher than the 57.1 percent that would be expected by chance.

Table 4-22. Summary of results of Pearson's Chi-square test of detect/non detect matches for organic contaminants at DNTS.

Compound	**Sample Pairs**	**Control Well Detects**	**Number of Mismatches**		**Pearson's Chi-Square Test**	
			Control=D Test=ND	Control=ND Test=D	Chi-Square	Probability
1,1,1-trichloroethane	74	30	3	2	51.1	0.0000
1,1,2-trichloroethane	78	13	3	3	35.7	0.0000
1,4-Dichlorobenzene	75	20	5	8	22.4	0.0000
Benzene	78	41	4	7	37.4	0.0000
cis-1,2-Dichloroethene	78	54	1	2	60.2	0.0000
Ethylbenzene	78	22	1	6	46.4	0.0000
MTBE	51	13	4	2	19.8	0.0000
Tetrachloroethene	78	42	6	5	37.3	0.0000
Toluene	78	27	4	5	40.4	0.0000

trans-1,2-Dichloroethene	78	16	6	8	14.9	0.0001
Trichloroethene	78	58	2	1	58.8	0.0000
Vinyl Chloride	78	43	6	4	40.1	0.0000
Xylene (m,p)	54	23	5	5	18.4	0.0000
Xylene (o)	30	16	3	4	6.4	0.0112

Summary

For the majority of the field parameters, inorganic analytes, and organic contaminants present at Dover AFB, there does not appear to be a systematic bias that can be associated with DP well construction. For the few analytes where there were statistically significant differences (excluding the questionable Specific Conductance values), the differences were generally not large in magnitude and most likely would not have impacted any management decision. Statistical analyses of the data for VOC concentrations near the detection limit also indicated that the performance of the DP and HSA wells was similar at this site.

There were not many sampling events for the statistical analyses of the five well types (i.e., comparing the Phase II wells with the older wells), so the statistical analyses are not as rigorous and the findings need to be treated with more caution. However, generally there were no statistically significant differences between the new DP wells and the HSA wells or between the new HSA wells and the older HSA wells for the organic and inorganic analytes present at Dover AFB. However, for a few field parameters and one inorganic analyte (Mn) there were statistically significant differences between the ¾-inch DP wells (with no filter pack) and the conventional wells. For Mn, spatial variability apparently accounts for much of this difference, since there also were statistically significant differences between the new and older HSA wells. For the other field parameters, these differences were generally not large in magnitude and would not have impacted any management decision.

NAVFAC ESC Results:

For Phase I, there were two sites at Port Hueneme referred to as “Cells A and B;” each comprised of four well clusters. At Cell A, each cluster contained three well types and all conformed to ASTM design standards. Each cluster contained a ¾-inch diameter DP well, a 2-inch diameter DP well, and a 2-inch diameter HSA control well. At Cell B, each cluster contained five well types including the three previously mentioned and two ¾-inch diameter DP wells, one with a conventionally designed pre-pack filter and the other with no pre-pack filter. For both cells, the screens were 2 feet in length for two clusters and 5 feet in length at the other two clusters.

For Phase II, none of the monitoring wells were sampled at Cell A because of on-going remediation efforts adjacent to the clusters. At Cell B, two additional wells were installed at two of the well clusters. These included a replicate 2-inch diameter HSA well and a replicate ¾-inch diameter ASTM-designed DP well with pre-pack filter.

Because of the differences in the well types sampled in Phases I and II, several different statistical analyses were conducted on the data to determine the significance of well type. Analyses included comparisons of the three ASTM-designed wells at Cells A and B (Phases I

and II data), analyses of the five wells at Cell B (Phases I and II data), and analyses of the seven wells at Cell B, including comparisons of the new replicate wells with the original wells (Phase II data only). The data set that contained the three ASTM-designed wells had the largest number of entries (with data from Cells A and B and from both Phases I and II). Therefore the statistical analyses conducted on these data sets are the most rigorous. The seven well comparisons provided a superior measure of the spatial heterogeneity associated with two identical well types, especially the two HSA wells in each well cluster.

Because the test design was more elaborate than at other sites, and because the MTBE data set only contained three missing values (with all values well above the detection limit), more thorough statistical analyses could be conducted on this data. Additional analyses allowed us to examine the impact of spatial heterogeneity (i.e., well cluster effects including location, sampling depth and screen length) and temporal effects (i.e., the effect of time or sampling event) on MTBE concentrations.

Field parameter data

The six field parameters measured at the Port Hueneme cells included DO, oxidation/reduction potential (ORP), pH, specific conductivity, temperature and turbidity. Table 4-23 gives the raw data for these parameters, and Table 4-24 provides the mean values for the three ASTM-designed wells. Generally, there is very good agreement between the mean values for the three well types. However, for three field parameters (DO, ORP, and Turbidity), the values for the ¾-inch diameter (ASTM) DP wells were statistically significantly lower than the values for the conventional 2-inch HSA wells (Table 4-24). For all three well types, the mean turbidity values were above the desired value of 10. When turbidity readings over 100 were removed from the data set (the new mean values are given in parentheses in Table 4-23), only the mean value for the ¾-inch DP wells was below 10 Nephelometric Turbidity Units (NTU). The mean values for the 2-inch DP wells and 2-inch HSA wells remained elevated due to the presence of a number of readings greater than 40 NTU.

Table 4-23. Mean values for field parameters for Cells A and B, Phases 1 and 2 at NAVFAC ESC.

	All ASTM Wells		
Analyte	**3/4-in. DP**	**2-in. DP**	**2-in. HS**
DO (mg/L)	**0.18***	0.26	0.32
ORP (mV)	**106***	123	124
pH	7.23	7.24	7.23
Spec. Cond. (m/Sm)	3.11	3.09	3.11
Temp. (°C)	21.6	21.8	21.8
Turbidity (NTU)	**11.6*** (8.2**)	21.5 (17.0**)	18.4 (16.0**)

*Significantly different from 2-inch HS well.

** Mean minus possible outliers with values > 100.

Table 4-24. Summary of statistical analyses of field parameter data for 3-well comparisons at NAVFAC ESC.

Parameter	N	Sig. Dif.?	Type of test	Probability	Sig. dif. from 2-in. HS well?	
					2-in. DP ASTM	3/4-in. DP ASTM
Dissolved Oxygen	56	**Yes**	Friedman RM-ANOVA on ranks	0.008	No	**Yes**
ORP	32	No	Friedman RM-ANOVA on ranks	0.205		
pH	56	No	Friedman RM-ANOVA on ranks	0.643		
Specific Conductance	56	No	Friedman RM-ANOVA on ranks	0.767		
Temperature	56	No	Friedman RM-ANOVA on ranks	0.48		
Turbidity	56	**Yes**	Friedman RM-ANOVA on ranks	0.002	No	**Yes**

Table 4-25 provides the mean values for the five well types at Cell B, including the three ASTM-designed wells and two additional ¾-inch diameter DP wells (one with a conventionally designed filter pack and one with no pre-pack filter). For DO, values were statistically significantly different (lower) for the ¾-inch ASTM-designed DP wells and for the ¾-inch DP wells with no filter pack when compared with the 2-inch HSA wells (Table 4-26). The mean turbidity value was very high for the ¾-inch DP wells with no filter pack and the mean values for the 2-inch DP wells and 2-inch HSA wells were also higher than the desired value of 10 NTU. These mean values are high because of the presence of a few (2 to 4) very high values that may be outliers. The mean values with these potential outliers removed are given in parentheses in this table. In contrast, the ¾-inch DP wells with the conventionally designed filter pack yielded consistently lower turbidity values, which were statistically significantly lower than those for the HSA well (Table 4-26).

Table 4-25. Mean values for field parameters for Cell B, Phases 1 and 2 at NAVFAC ESC.

Analyte	3/4-in. DP ASTM	3/4-in. DP Conv. pack	3/4-in. DP No-pack	2-in. DP ASTM	2-in HS ASTM
DO (mg/L0	**0.21***	0.23	**0.16***	0.30	0.39
ORP (mV)	106	108	112	123	124
pH	7.33	7.36	7.20	7.34	7.37
Spec. Cond. (m/Sm)	3.05	3.04	3.04	3.02	3.05
Temp. (°C)	21.9	21.8	21.9	21.7	21.7
Turbidity (NTU)	6.9	**7.1***	69.0 (15.9**)	22.2 (14.6**)	17.8 (16.9**)

* Significantly different from 2-in. HS well

**Minus possible outliers with values > 100.

Table 4-26. Summary of statistical analyses of field parameter data for Site B, 5-well comparisons at NAVFAC ESC.

					Significantly different from control well?			
					2-in. DP	3/4-in. DP	3/4-in. DP	3/4-in. DP
Parameter	**N**	**Sig. Dif.?**	**Type of test**	**Prob.**	**ASTM**	**ASTM**	**Conv. Pack**	**No filter pack**
DO	41	**Yes**	Friedman RM-ANOVA on ranks	<0.001	No	**Yes**	No	**Yes**
ORP	32	No	Friedman RM-ANOVA on ranks	0.396				
pH	44	No	Friedman RM-ANOVA on ranks	0.426				
Spec. Cond.	44	No	Friedman RM-ANOVA on ranks	0.073				
Temp.	32	Yes/No	Friedman RM-ANOVA on ranks	0.044	No	No	No	No
Turbidity	32	**Yes**	Friedman RM-ANOVA on ranks	<0.001	No	No	**Yes**	No

Inorganic analytes

The inorganic analytes that were measured during Phase I included alkalinity, boron, calcium chloride, fluoride, iron, magnesium, manganese, potassium, sodium sulfate, total hardness, and total dissolved solids. During most of Phase II, the analyses of inorganics were limited primarily to metals that might leach from the stainless steel components of the wells. Specifically, the metals that were analyzed included: barium, cadmium, chromium, copper, iron, lead, manganese, molybdenum, and nickel. Table 4-27 provides the mean values for the three ASTM-designed wells.

Results for the three ASTM-designed wells (Table 4-27) suggest that there is generally very good agreement between the mean values for all the analytes. Statistical analyses conducted on this data revealed that there were no statistically significant differences for the majority of the

analytes (11 out of 13) (Table 4-28). There were statistically significant differences between the 2-inch diameter HSA wells and the 2-inch diameter DP wells for alkalinity, manganese, and potassium. However, in all cases, the differences in the mean values were relatively small in magnitude and would not have impacted any management decision.

Table 4-27. Mean concentrations of inorganic analytes in the three ASTM designed wells at NAVFAC ESC.

Analyte	3/4-in. DP	2-in. DP	2-in. HS
Alkalinity	428	**424***	431
Boron	2.5	2.4	2.4
Calcium	384	380	382
Chloride	84	83	84
Fluoride	1.05	1.08	1.09
Iron	3.5	3.9	3.7
Magnesium	147	145	145
Manganese	2.41	**2.50***	2.35
Potassium	6.3	**6.1***	6.9
Sodium	261	258	260
Sulfate	1540	1550	1560
Total hardness	1660	1670	1690
TDS	2880	2880	2890

***** Statistically significantly different from 2-in HS wells.

Table 4-28. Summary of statistical analyses of inorganic data from ASTM-designed wells (3-well data) at NAVFAC ESC.

Analyte	N	Sig. Dif.?	Type of test	Prob.	Sign. Dif. with 2-in HS? 2-in. DP	3/4-in. DP
Alkalinity	32	**Yes**	Friedman RM-ANOVA on ranks	0.021	**Yes**	No
Boron	32	No	Friedman RM-ANOVA on ranks	0.294		
Calcium	32	No	Friedman RM-ANOVA on ranks	0.575		
Chloride	32	No	Friedman RM-ANOVA on ranks	0.11		
Fluorine						
Iron	26	No	Friedman RM-ANOVA on ranks	0.881		
Magnesium	32	No	Friedman RM-ANOVA on ranks	0.261		
Manganese	36	**Yes**	Friedman RM-ANOVA on ranks	0.034	**Yes**	No
Potassium	32	**Yes**	Friedman RM-ANOVA on ranks	<0.001	**Yes**	No
Sodium	32	No	Friedman RM-ANOVA on ranks	0.193		
Sulfate	32	No	Friedman RM-ANOVA on ranks	0.727		
Zinc	8	No	One-way RM-ANOVA on data	0.339		

Total hardness	32	No	Friedman RM-ANOVA on ranks	0.285
TDS	32	No	One-way RM-ANOVA on data	0.755

When the inorganic and metal concentrations in samples from the four DP well types (Cell B wells) were compared with the HSA wells, again there were no statistically significant differences for the majority of the analytes (10 out of 14). Mean concentrations for the five well types are shown in Table 4-29 and the results of the statistical analyses are shown in Table 4-30. There were statistically significant differences for alkalinity, and chloride, manganese, and potassium concentrations. The 2-inch diameter DP wells had statistically significant differences for alkalinity, and chloride, and potassium concentrations. For the other well types, there were only one or two analytes where a statistically significant difference was found. However in all cases where statistically significant differences were found, the differences in the magnitude of the mean values were not large, and management decisions would not have been impacted. Cadmium, chromium, copper, lead, and nickel were not detected in these wells.

Table 4-29. Mean concentrations of inorganic analytes in 5 well types at NAVFAC ESC.

Well type	3/4-in. DP	3/4-in. DP	3/4-in. DP	2-in DP	2-in. HS
Filter pack	**ASTM**	**Conventional**	**No filter pack**	**ASTM**	**ASTM**
Analyte					
Alkalinity	411	407	416	**408***	420
Barium	21.25	22.0	38.3	43.5	25.5
Boron	2.2	2.2	2.2	2.2	2.2
Calcium	363	355	358	364	363
Chloride	77	79	76	**75***	79
Fluoride	1.03	1.01	1.05	1.08	1.04
Iron	4.3	3.8	5.1	4.0	4.5
Magnesium	142	141	143	141	140
Manganese	2.32	2.42	**2.52***	2.46	2.32
Molybdenum	42	49.5	46.5	42.5	47
Potassium	**6.8***	**7.1***	**7.1***	**6.5***	7.6
Sodium	253	255	253	250	253
Sulfate	1460	1460	1470	1490	1480
Total hardness	1600	1560	1570	1610	1590
TDS	2740	2730	2750	2760	2730
Zinc	5.0	4.8	12	9.5	4.5

*Statistically significantly different from 2-in HS well.

Table 4-30. Summary of statistical analyses of inorganic data for Site B comparing 5 well types at NAVFAC ESC.

						Significantly different from control well?				
						2-in. HS	2-in. DP	3/4-in. DP	3/4-in. DP	3/4-in. DP no-pack
Analyte	N	Sig. Dif.?	Type of test	Prob.	Power	ASTM	ASTM	ASTM	Conv.	
Alkalinity	16	**Yes**	Friedman RM-ANOVA on ranks	<0.001			**Yes**	**Yes**	No	No
Barium	4	No	One-way RM-ANOVA on data	0.36						
Boron	16	No	Friedman RM-ANOVA on ranks	0.64						
Calcium	16	No	Friedman RM-ANOVA on ranks	0.145						
Chloride	16	**Yes**	Friedman RM-ANOVA on ranks	0.046			**Yes**	No	No	No
Fluoride	8	No	One-way RM-ANOVA on data	0.358	0.074					
Iron	14	No	Friedman RM-ANOVA on ranks	0.086						
Magnesium	16	No	Friedman RM-ANOVA on ranks	0.406						
Manganese	20	**Yes**	One-way RM-ANOVA on data	0.008			No	No	No	**Yes**
Molybdenum	4	No	One-way RM-ANOVA on data	0.074						
Potassium	16	**Yes**	One-way RM-ANOVA on logs	<0.001			**Yes**	**Yes**	**Yes**	**Yes**
Sodium	16	No	Friedman RM-ANOVA on ranks	0.813						
Sulfate	16	No	Friedman RM-ANOVA on ranks	0.655						
Ttl. hardness	16	No	Friedman RM-ANOVA on ranks	0.521						
TDS	16	No	One-way RM-ANOVA on data	0.681						

For Phase II, two replicate wells were installed at two selected well clusters. The additional wells consisted of a replicate 2-inch diameter HSA well (i.e., replicate of the control well) and a replicate ¾-inch DP well with a conventionally designed filter pack. Although samples were only collected twice in these wells, statistical analyses were conducted on two metals: iron and manganese (Table 4-31). These analyses revealed that there was no statistically significant difference between the replicate and original HSA wells or between the replicate and original ¾-inch DP wells (with conventionally designed filter pre-pack filters). However, for iron, there was a statistically significant difference between the ¾-inch ASTM DP well and the *new* 2-inch HSA well, and between the original ¾-inch DP well with a conventional filter pack and the *new* 2-inch HSA well (i.e., the mean concentration was highest for the new HSA wells). These statistically significant differences were not observed between the new ¾-inch DP wells with a conventional filter pack and the new 2-inch HSA wells. Although the magnitude of these

differences was small, these statistically significant differences demonstrate the effect of spatial heterogeneity on analyte concentrations in a well cluster.

Table 4-31. Summary of statistical analyses of metals collected from all 7 wells at NAVFAC ESC.

Analyte	N	Sig. Dif.?	Type of test	Probability	Power**	
Iron	4	**Yes**	RM-ANOVA- raw data	0.01	0.78	
Manganese	4	No	RM-ANOVA- raw data	0.857		
	Significant difference with original 2-in. HS well?					
	2-in. DP ASTM	**3/4-in. DP ASTM**	**3/4-in. DP Conv. filter pack**	**3/4-in. DP No filter pack**	**New 3/4-in. DP Conv. pack**	**New 2-in. HS ASTM**
Iron	No	No	No	No	No	No
	Significant difference with *new* 2-in HS well?					
	2-in. DP ASTM	**3/4-in. DP ASTM**	**3/4-in. DP Conv. filter pack**	**3/4-in. DP No filter pack**	**New 3/4-in. DP Conv. pack**	
Iron	No	**Yes**	**Yes**	No	No	

<u>Organic contaminant, MTBE</u>

MTBE was the only contaminant present at this site. Table 4-32 provides the mean values for the three ASTM-designed wells, the five wells at Cell B, and the seven wells at Cell B (including the replicate HSA and ¾-inch ASTM-designed DP wells). In all cases, the mean values for the various well types agreed well, and statistical analyses revealed that there were no statistically significant differences between the concentrations of MTBE in the various DP well types when compared to the control HSA wells (Table 4-33). This finding includes that there were no statistically significant differences between the concentration of MTBE in the *new* 2-inch HSA wells when compared to any of the other wells (including the original 2-inch diameter HSA well), or between the concentration of MTBE in the *new* ¾-inch ASTM-designed DP wells when compared to any of the other well types.

Table 4-32. Mean concentrations of MTBE in wells at Port Hueneme.

		Mean concentration (µg/L)						
# of wells	N	¾-in. DP ASTM	*New* ¾-in DP ASTM	¾-in. DP Conv.	¾-in. DP No-pack	2-in. DP ASTM	2-in. HS ASTM	*New* 2-in. HS ASTM
3	72	255				243	248	
5	52	338		364	347	322	331	
7	16	495	503	497	494	419	490	499

Conv.= conventional filter pack

Table 4-33. Summary of statistical analyses of MTBE data for NAVFAC ESC.

# Wells	N	Type of test	Sig. Dif.?	Prob.
3	72	Friedman RM-ANOVA[1]	No	0.053
5	52	Friedman RM-ANOVA[1]	No	0.119
7	16	Friedman RM-ANOVA[1]	No	0.342

[1]on ranked data

The Cell B design was more elaborate than most of the other sites, and consisted of four clusters, each with five wells of different types. The wells in the different clusters were screened in different depth ranges. Samples were taken for all 13 sampling rounds, ranging from 10/24/2000 to 5/27/2005, for all 20 wells that were established at the beginning of the study, leading to a potential sample size of 260 observations. Only 3 samples are missing, and all of the remaining samples are substantially above the non-detect level, so the final dataset consists of 257 numeric observations. Given the detailed design, the nearly complete sampling, and the fact that the concentration data were approximately normally distributed, this dataset was amenable to more thorough analyses.

An ANOVA was employed to attempt to identify factors that produce consistent variations in average concentrations. Three factors were considered as being potentially important and were included in the ANOVA. The first factor was time, as represented by sampling event number. Most of the sampling events were done at about three-month intervals, except for a gap of about 18 months between the first and second phases. As a result of the gap, it was deemed better to treat the sampling events as discrete levels in a categorical factor, rather than attempting to estimate numeric trends as a function of continuous time. This factor measured the degree to which concentrations averaged over all the wells in Cell B vary over time.

The second factor included was well cluster. This factor captured differences between the averages for each cluster and the overall Cell B average that persisted through time. Any variations attributed to the cluster factor could be related to either horizontal trends in concentrations (since the clusters are in different locations) or vertical trends in concentrations (since all of the wells within a cluster were screened at the same depth ranges and different screen ranges were established for each cluster).

The third factor was well type. The five different well types included: 1) ¾ inch Direct-push, No Filter Pack; 2) ¾ inch Direct-push, ASTM Design Pre-pack; 3) ¾ inch Direct-push, Conventional Design Pre-pack; 4) 2 inch Direct-push, ASTM Design Pre-pack; 5) 2 inch HSA, ASTM Design, Tremmied. This factor would measure any differences in average concentrations for different well types that were consistent over time and across all of the well clusters (depth ranges). Type 5 is the current standard, so average differences between each of the four types of DP wells and the HSA wells were of particular interest.

The full balanced design would consist of 5 well types for each of 4 clusters (depth ranges) for each of 13 sampling events, for a total of 260 observations. As noted above, three lab samples

were missing, so there were actually 257 total observations. This slight degree of unbalance did not produce any noticeable problems in the statistical analysis and testing.

The basic statistics are presented in the ANOVA table (Table 4-34). By far the most striking result was that fully 72 percent of the total variance was captured by the sample event factor. In other words, a large proportion of the variability was associated with temporal changes that were consistent over all of the wells in the site. The temporal trends are readily apparent in the box plot of MTBE concentrations vs. sample event (Figure 4-1). Concentrations were relatively low, around 100 μg/L to 150 μg/L, over the first four sampling events, which occurred from October 2000 through August 2001. The last sampling event of the first phase, taken in November 2001, produced a substantially higher average concentration of more than 300 μg/L. This appeared to signal the start of a rising trend that continued during the 18 month hiatus between the first and second phases, as all of the sampling events over the period from July 2003 through November 2004 produced average concentrations in the 400 μg/L to 500 μg/L range. There is some indication that a downward trend may have begun in 2005 as the last samples, taken in March and May of 2005, showed the lowest average concentrations since 2001.

Table 4-34. Partitioning of sum of squares for ANOVA model for NAVFAC ESC MTBE data.

Source	DF	Sum of Sq	Percent	Mean Sq	F Value	Pr(F)
Sample Event	12	5,996,389	72.0%	499,699.1	63.87	0.0000
Cluster/Depth Range	3	418,460	5.0%	139,486.8	17.83	0.0000
Well Design	4	60,526	0.7%	15,131.4	1.93	0.1055
Residual	237	1,854,199	22.3%	7,823.6		
Total	256	8,392,573	100.0%	32,537.4		

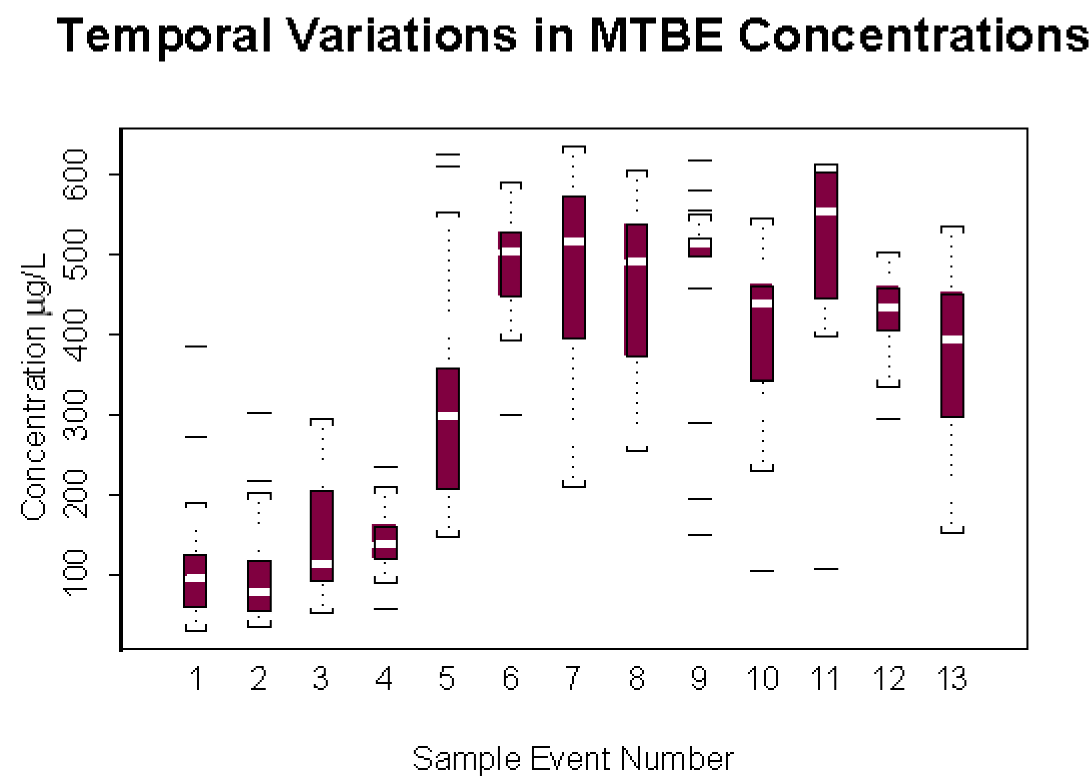


Figure 4-1. Box and Whisker plots showing MTBE concentrations for each Port Hueneme sampling event.

In all of the box and whisker plots the upper and lower limits of the vertical boxes are placed at the upper and lower quartiles, and the white bars within the boxes show the values of the medians. The brackets (whiskers) at the ends of the dotted lines are placed at the nearest values not beyond 1.5 times the interquartile ranges (vertical extents of the boxes) away from the quartiles. The horizontal line segments beyond the whiskers show individual values that fall outside the designated range.

The cluster/depth range factor was also significant, explaining about 5 percent of the total sum of squares. Figure 4-2 shows that Cluster B4 had the highest mean concentration (approximately 400 mg/L), and B2 had the lowest mean concentration (<300 mg/L). In terms of depth, the highest mean concentration occurred in one of the deeper clusters (the 12.5 to 17.5 feet depth of B4), while the shallowest depth (7 to 12 feet of B2) had the lowest mean concentration. In contrast, the depths of the screens in Cluster B1 were 10 to 12 feet, and were 16 to 18 feet in Cluster B3.

Figure 4-2. Box and Whisker plot showing MTBE concentrations in the four Hueneme well clusters.

Consistent with the previous ANOVA, these analyses also found that well type was not significant at the 0.05 level. This means that there were no statistically significant differences between mean concentrations measured in the five types of wells that were consistent over time (i.e., for the entire demonstration) and for all well clusters (depth ranges). Figure 4-3 shows that there were some differences between the mean values for the various well types, but they were small in comparison to the range of variation within each well type over time and from well cluster to well cluster.

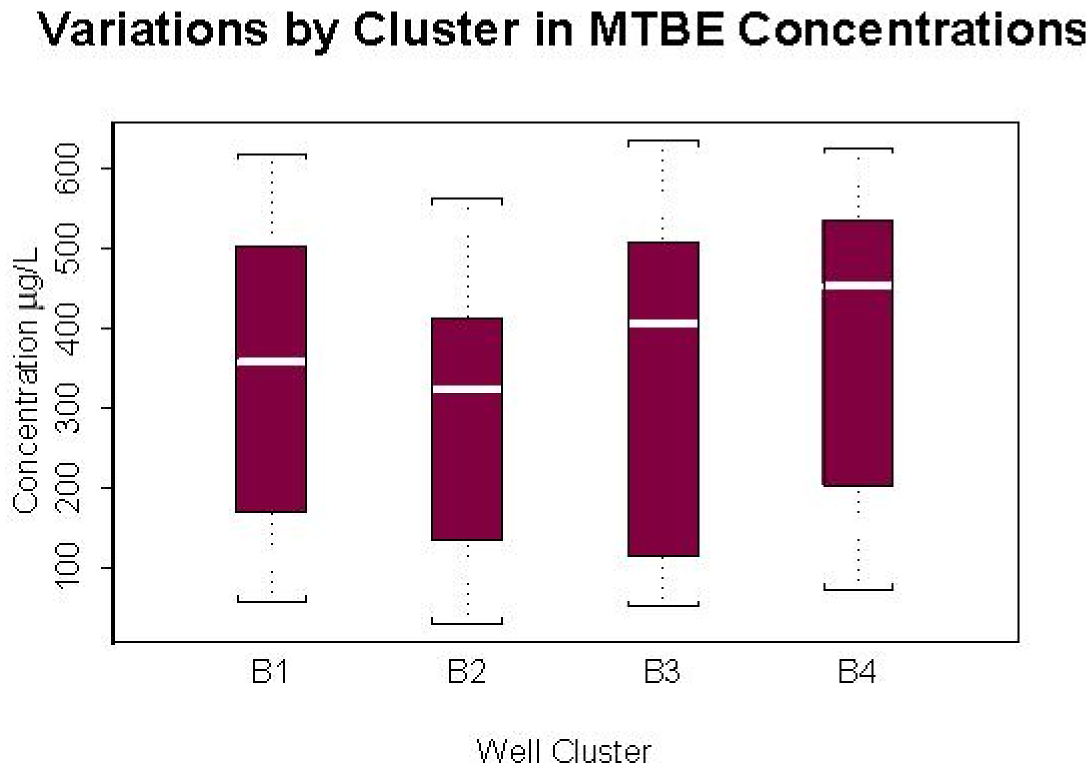


Figure 4-2. Box and Whisker plot showing MTBE concentrations in the four Hueneme well clusters.

Consistent with the previous ANOVA, these analyses also found that well type was not significant at the 0.05 level. This means that there were no statistically significant differences between mean concentrations measured in the five types of wells that were consistent over time (i.e., for the entire demonstration) and for all well clusters (depth ranges). Figure 4-3 shows that there were some differences between the mean values for the various well types, but they were small in comparison to the range of variation within each well type over time and from well cluster to well cluster.

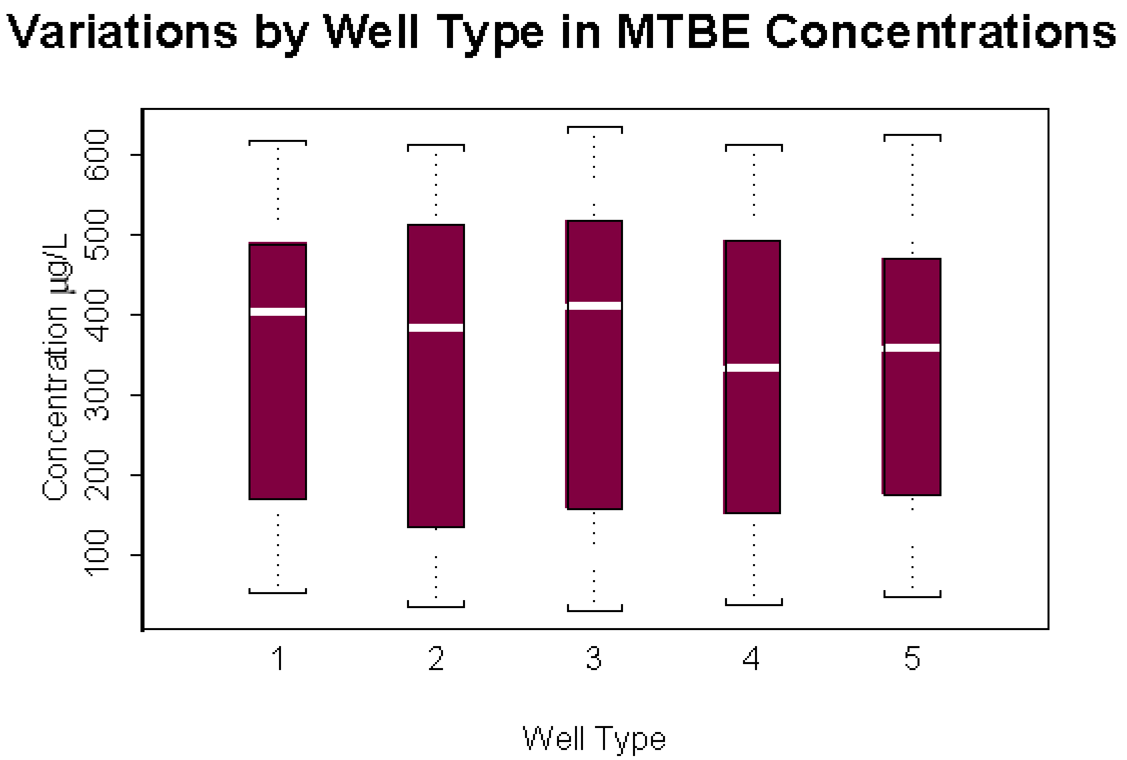


Figure 4-3. Box and Whisker plot showing MTBE concentrations for the five Hueneme well types.

Pairwise comparisons between each of the DP wells and the standard HSA wells are shown in Table 4-35. The largest differences between the mean for the HSA wells and the four DP wells were for the ¾-inch DP wells with a conventionally designed pre-pack filter (that was approximately 20 µg/L higher than the mean for the conventional wells, and the 2-inch ASTM-designed DP pre-pack wells that was approximately 20 µg/L lower than the mean for the conventional wells). Neither of these differences was large enough to achieve significance at the 0.05 level.

Table 4-35. Analysis of pairwise differences between DP wells and HSA wells for NAVFAC ESC MTBE data.

2" HSA vs.	Mean Diff.	Std. Error	t value	Prob.
3/4" DP No-pack	11.9	11.2	1.07	0.287
3/4" DP ASTM	-0.2	11.1	-0.01	0.988
3/4" DP Conv.	21.1	11.0	1.92	0.056
2" DP ASTM	-20.9	11.0	-1.90	0.058

Because well type did not significantly affect analyte concentrations, additional correlation analyses were used to determine whether the MTBE concentrations from each of the DP wells correlated with analyte concentrations from the conventional HSA wells. These analyses were conducted on the data from all the clusters. Figures 4-4 through 4-7 are scatter plots that show these comparisons for each of the DP well types and for each well cluster. These plots represent

the correlation differences between drilled and pushed wells due to all categorical variability factors, including temporal, spatial and well design. These should not be confused with ANOVA results that demonstrate very low variability due to well design only. All of the DP wells showed significant correlations with the conventional HSA wells. It was noteworthy that the MTBE concentrations obtained from different DP well designs showed such strong linear correspondence with the conventional wells. This is a powerful result because it indicates that not only are concentrations comparable in paired conventional and DP wells, but that the signs and magnitudes of variations about the mean concentrations also correlate well.

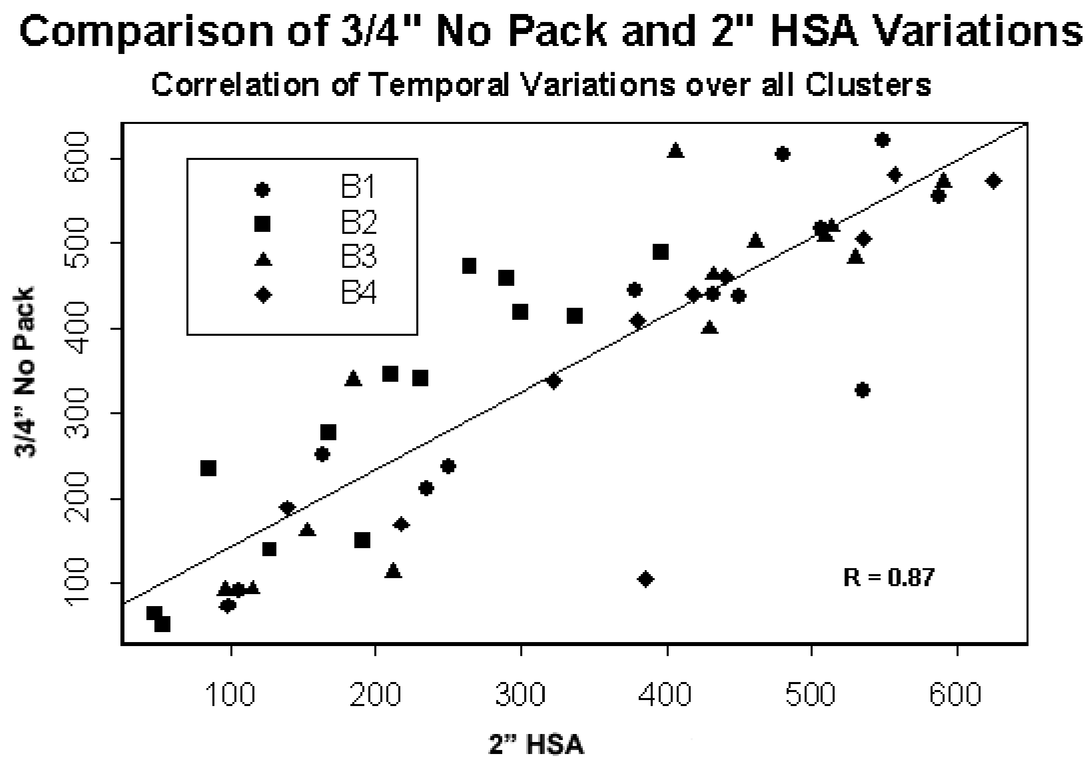


Figure 4-4. Comparison of Hueneme MTBE concentrations (ppb) in ¾ inch No-pack DP Wells and 2 inch Control Wells Over All Measurement Events.

Figures 4-4 through 4-7 show pairwise scatter plots for each of the DP well designs against the 2 inch standard well design from the same cluster. The correlations and best-fit lines were calculated for well pairs over all clusters, although the cluster membership of each point is represented by symbol differences on the plots. All of the DP well designs showed significant correlations with the standard well design. At a basic level, this was to be expected, given the large proportion of the overall sum of squares that was explained by the sampling event factor in the ANOVA. Nonetheless, it was noteworthy that the MTBE concentration measurements obtained at the same times from different well designs showed such strong linear correspondence. This is a powerful result because it indicates that not only are mean concentrations comparable in paired control and test wells, but that the signs and magnitudes of variations about the mean concentrations also track each other closely.

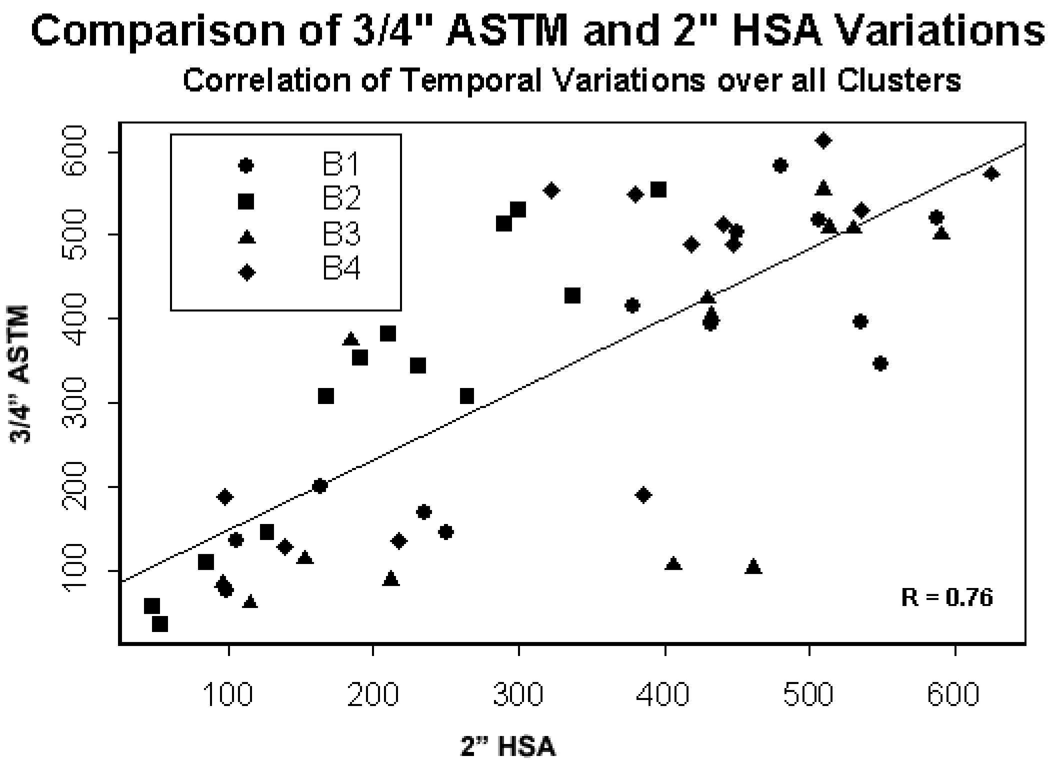


Figure 4-5. Comparison of Hueneme MTBE Concentrations (ppb) in ¾ inch ASTM DP Wells and 2 inch Control Wells Over All Measurement Events.

The relationship between 3/4 inch direct-push no-pack (type 1) and the 2 inch inch standard type had the strongest with a correlation of 0.86 (r-square of 0.75). The relationship between well the ¾-inch ASTM DP wells and the conventional HSA wells (Figure 4-5) showed a somewhat less but still statistically significant correlation (r = .76) and there were some distinctive outliers. The relationship between the ¾-inch conventionally designed DP wells and the conventional HSA wells (Figure 4-6) also showed good correlation (r = .82).

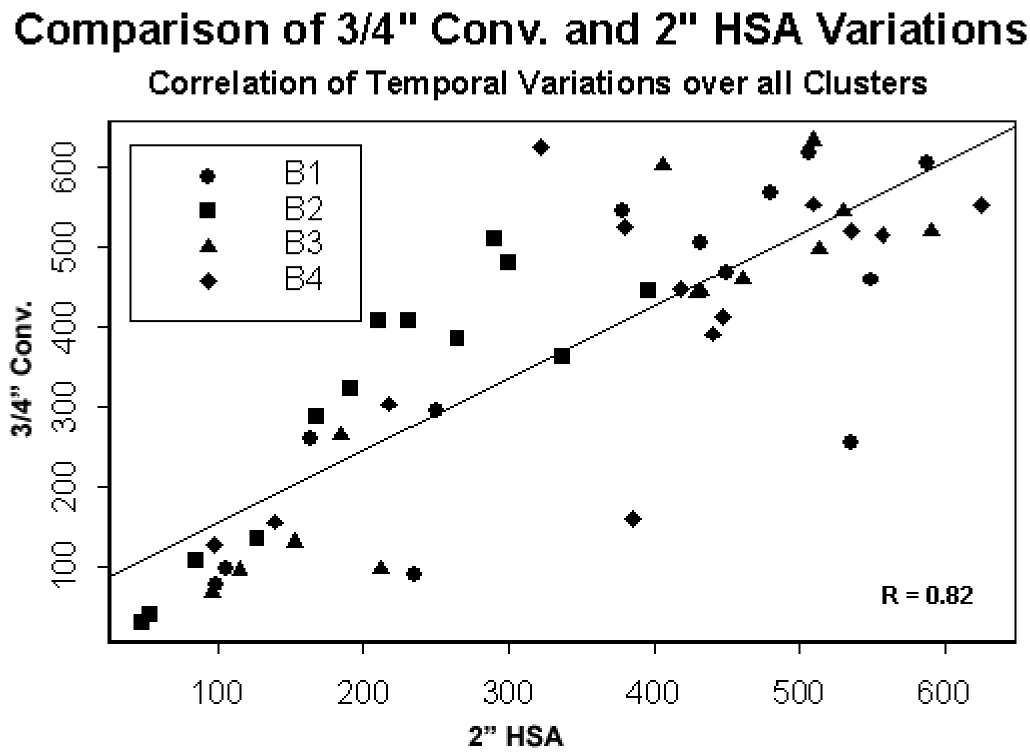


Figure 4-6. Comparison of Hueneme MTBE Concentrations (ppb) ¾ inch Conventional DP Design and 2 inch Control Wells Over All Measurement Events.

The relationship between the 2-inch DP wells and the 2-inch HSA wells was the poorest (Figure 4-7). Although the correlation was still highly significant, less than half of the variance was explained by the linear regression, and the slope of the best-fit line was significantly less than 1:1. Both results were produced primarily by the distinct cluster of six points in the lower right hand corner of the scatter plot. These points represent samples with substantially higher concentrations in the HSA wells than in the DP well in the same clusters on the same dates. If these six points were removed, the correlation would increase to greater than 0.80 and the slope would be nearly 1. However, there does not seem to be any obvious reason for removing them.

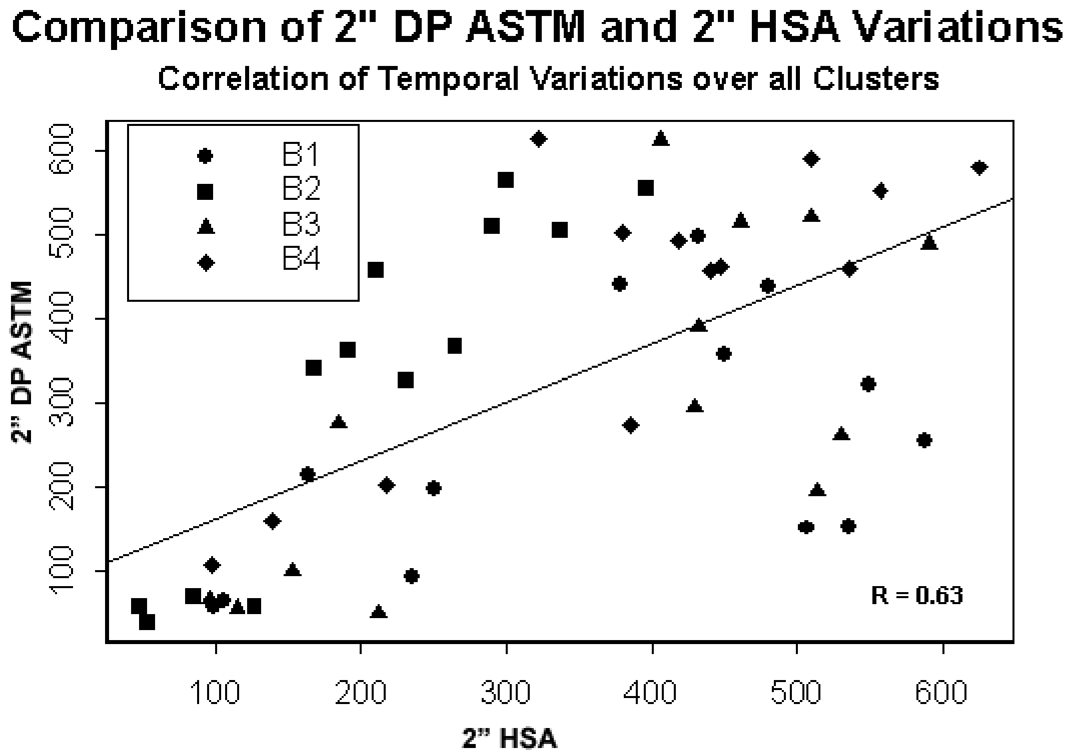


Figure 4-7. Comparison of Hueneme MTBE Concentrations (ppb) in 2 inch DP ASTM Wells and 2 inch Control Wells Over All Measurement Events.

From a qualitative perspective, perhaps one of the most significant observations relates to how experimental DP well concentrations rank relative to the control drilled hollow stem auger well and the duplicate of this drilled well during any particular sampling event. For instance, Figure 4-8 displays MTBE concentrations for wells in Port Hueneme Cluster B1 for September 2003. Notice that none of the experimental well concentrations falls within the range of concentrations exhibited by the control drilled well and its duplicate (549 to 586 ppb). On the contrary, wells from Cluster B4 analyzed for that same September 2003 sampling event exhibit a very different ranking, whereby all experimental wells fall within the range of concentrations exhibited by the control drilled well and its duplicate (459 to 625 ppb, Figure 4-9). Interestingly, duplicate DP wells exhibit a relatively significant concentration range for Cluster B1 (346 to 530 ppb), but not for Cluster B4 (567 to 574 ppb) during that same sampling event.

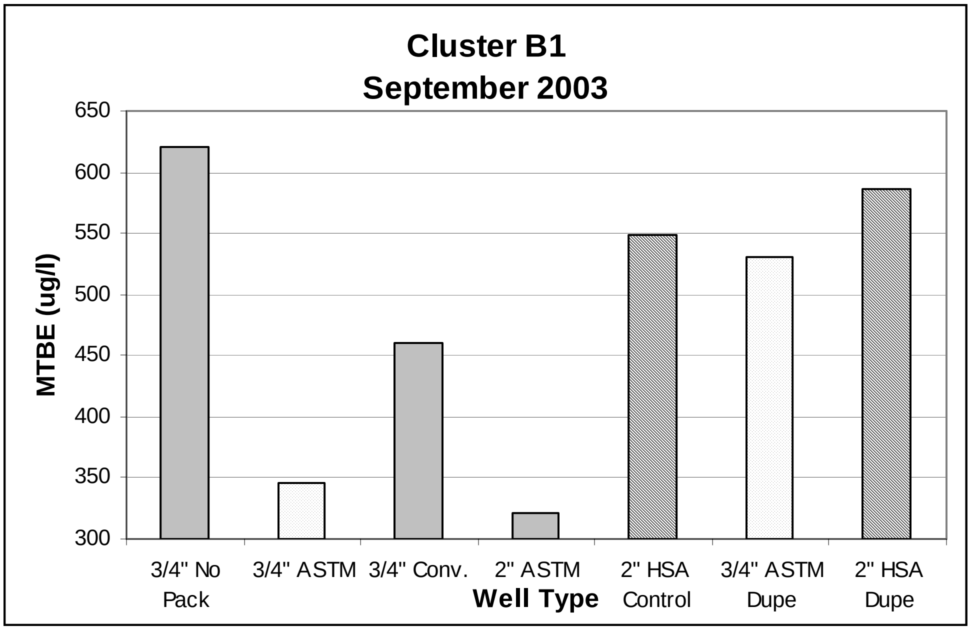


Figure 4-8. MTBE Concentrations for Port Hueneme Cluster B1, September 2003. Drilled control and duplicate wells are depicted with diagonal stripes, while duplicate pushed wells are depicted with dotted pattern.

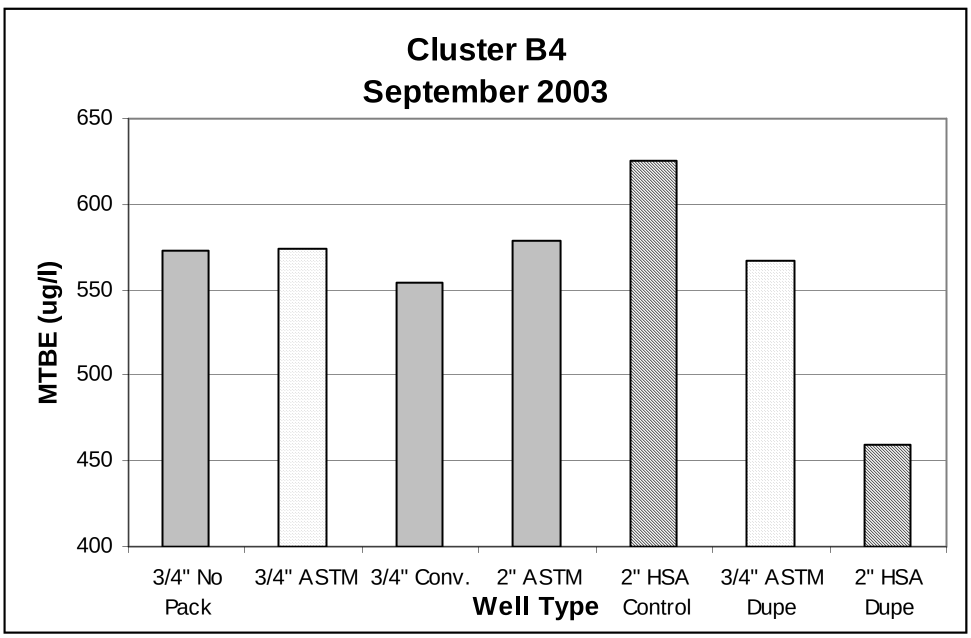


Figure 4-9. MTBE Concentrations for Port Hueneme Cluster B4, September 2003. Drilled control and duplicate wells are depicted with diagonal stripes, while duplicate pushed wells are depicted with dotted pattern.

These random ranking patterns were observed throughout the duration of Phase II sampling events. The fact that identically designed and installed wells can sometimes exhibit relatively large concentration ranges suggests that spatial heterogeneity with respect to solute plume concentration distribution imparts variability upon the observations. Since there is no recognizable pattern associated with subsequent observations, temporal variability also plays a significant role. These qualitative observations are consistent with analyses of box plots and the more rigorous ANOVA tests.

<u>Summary</u>

These findings demonstrated that representative concentrations of MTBE were recovered from DP wells that varied in diameter and filter pack design. Systematic differences between concentrations measured at DP and conventional wells were small relative to temporal variations and were not statistically significant. The temporal variations measured at DP wells generally tracked closely those measured at adjacent conventional wells. Thus, management decision should be consistent at this site regardless of the well type used. Representative concentrations of inorganic analytes were also recovered from the various DP well types. In the relatively few instances where statistically significant differences were found in analyte concentrations, the differences were not large in magnitude and would not have impacted management decisions regarding whether or not to remediate. Statistical analyses of the purge parameter data also indicated that there was generally good agreement with the data from the DP wells and the conventional HSA wells. However, the smaller ¾-inch pre-pack DP wells did consistently display lower turbidity values, and all three smaller diameter (3/4-inch diameter) DP wells exhibited slightly lower dissolved oxygen concentrations.

Hanscom Results:

The two well types at this location were 2-inch diameter HSA wells with a conventionally designed filter pack and 2-inch diameter DP wells with no pre-pack. Because this site was undergoing active remediation and concentrations of the organic contaminants in the wells began to approach the detection levels towards the end of Phase I, so samples were not collected at this site during Phase II.

<u>Field parameter data</u>

The six field parameters measured at this site included temperature, pH, turbidity, Specific Conductance, dissolved oxygen (DO), and oxidation/reduction potential (ORP). Table 4-36 gives the mean concentrations for these parameters. There was no significant difference between these two well types for the majority (5/6) of these parameters (Table 4-37). DO was the only parameter where there was a statistically significant difference between the concentrations in the two wells. Concentrations were statistically significantly higher in the DP wells. Although this difference was not large in magnitude, analysis of the data given in Table 4-38 reveals that there were substantial differences in the values for the two well types at two locations (MWZ-23, OW2-6). In both cases, DO levels were considerably lower in the HSA wells. When the data for those two sites is removed from the data set, there is no longer a significant difference between the DO levels in these wells (Table 4-36). It is not clear what may have been the cause of these differences.

Although, no significant difference was found between the turbidity values for the DP wells relative to the conventional HSA wells, the mean values were very high and reflect the presence of a few values that were extremely high. These values resulted when the wells were purged to dryness and then sampled after recovery. These values were considered to be outliers and were removed from the data set and revised mean values were calculated (also provided in Table 4-36). Clearly, there is better agreement after these values were removed from the data set.

Table 4-36. Mean values for purge parameters in Hanscom wells.

	Mean values	
Parameter	HS	DP
Temperature	11.9	12.6
pH	6.3	6.0
Specific Conductance	0.39	0.41
ORP	40.8	89.4
DO	3.48*	4.89*
DO minus 2 locations	4.22	4.70
Turbidity	70	151
Turbidity minus outliers	12.0	9.4

*There was a statistically significant difference between the values in the two well types.

Table 4-37. Results of statistical analyses of purge parameter data at Hanscom AFB.

Parameter	N	Sig. Dif.?	Type of test	Prob.	Power
Turbidity	30	No	Paired t-test on log data	0.147	0.176
Temp.	30	No	Wilcoxon Signed Rank	0.51	
pH	30	No	Wilcoxon Signed Rank	0.48	
Spec. Cond.	30	No	Wilcoxon Signed Rank	0.355	

DO	30	**Yes**	Paired t-test on data	0.015	0.63
ORP	30	No	Wilcoxon Signed Rank	0.139	

Table 4-38. Dissolved oxygen concentrations in Hanscom wells.

		DO mg/L	
Date Collected	**Location**	**HS**	**DP**
May-01	B107	14.4	13.8
Jul-01	B107	7.91	11.7
Oct-01	B107	3.12	5.58
Nov-00	MWZ-04	0.54	1.47
May-01	MWZ-06	0.34	0.33
Jul-01	MWZ-06	0.29	0.3
Oct-01	MWZ-06	0.43	0.92
May-01	MWZ-11	0.55	0.45
Jul-01	MWZ-11	0.37	0.58
Nov-00	MWZ-23	**0.7**	**9.16**
Jan-01	MWZ-23	**0.32**	**8.53**
Oct-00	OW2-2	0.24	0.3
Nov-00	OW2-2	0.51	5.84
Jan-01	OW2-6	**3.64**	**6.61**
May-01	OW2-6	**1.37**	**2.04**
Jul-01	OW2-6	**0.42**	**1.17**
Oct-01	OW2-6	**0.37**	**5.13**
Nov-00	RAP2-2T	0.64	0.48
Jan-01	RAP2-2T	0.96	0.25
May-01	RAP2-2T	1.73	2.94
Jul-01	RAP2-2T	0.28	1.8
Oct-01	RAP2-2T	0.26	2.54
May-01	RAP2-4S	12.62	11.1
Jul-01	RAP2-4S	4.21	8.17
Oct-01	RAP2-4S	8.33	7.16
Nov-00	RFW-11	11.43	4.14
Jan-01	RFW-11	5.31	8.12

May-01	RFW-11	11.12	11.4
Jul-01	RFW-11	8.72	8.55
Oct-01	RFW-11	3.37	6.11

Inorganic Analytes

The 10 inorganic parameters measured at Hanscom AFB included alkalinity, calcium, chloride, magnesium, manganese, potassium, sodium, sulfate, total dissolved solids, and total hardness. The mean values for these analytes are given in Table 4-39. For almost all of these parameters (9 of 10), there was no statistically significant difference between the well types (Table 4-40). Sodium was the only analyte where well type exhibited a statistically significant difference, but the difference in the mean values was not large. This data contains a few unusually high values that appear to have been outliers (Table 4-40). When these few values were removed from the sodium data, a paired *t*-test indicated that there was no statistically significant difference between the two well types.

Table 4-39. Mean concentration of inorganic analytes in Hanscom wells.

	Mean Concentration (mg/L)		Revised Mean Conc.	
Analyte	**HS**	**DP**	**HS**	**DP**
TDS	133	160		
HARD	69	94		
Calcium	21.5	28.7		
Alkalinity	35.5	50.4	36[1]	44[1]
Chloride	11.2	23.7	12[2]	13.3[2]
Magnesium	3.90	5.60		
Manganese	0.92	1.04		
Potassium	2.21	2.60		
Sodium	**9.8**	**13.9**	8.8[2]	9.9[2]
Sulfate	42.9	35.0	38.4[1]	36.7[1]

[1] minus one outlier

[2] minus two outliers

*There was a statistically significant difference between the values in the two wells

Table 4-40. Summary of Statistical Analyses of Hanscom Inorganic Data.

Analyte	Sign. Diff?(95%CL)[1]	Type of test	Prob.	Power
TDS	No	Paired-*t* test on log data	0.115	0.227
HARD	No	Paired-*t* test on log data	0.213	0.114
Calcium	No	Wilcoxon Signed Rank test	0.551	
Alkalinity	No	Paired-*t* test on log data	0.202	0.123
Chloride	No	Paired-*t* test on log data	0.158	0.166
Magnesium	No	Paired-*t* test on log data	0.157	0.168
Manganese	No	Paired-*t* test on log data	0.235	0.099
Potassium	No	Paired-*t* test on log data	0.195	0.129
Sodium	Yes	Wilcoxon Signed Rank test	0.048	
Sulfate	No	Paired-*t* test on log data	0.864	0.05

<u>Organic Contaminants</u>

Organic contaminants at this site included benzene, *cis*-1,2-dichloroethylene, ethylbenzene, *p*-dichlorobenzene, trichloroethylene, toluene, *o*-xylene, and vinyl chloride. Table 4-41 presents the mean concentrations for these analytes. Statistical analyses of the data for each of the analytes revealed that there were no statistically significant differences between the conventional HSA and DP wells. This finding is borne out by examining the mean values. There is generally close agreement between the mean values for the two well types with the exception of toluene and vinyl chloride. For these two analytes, the disparities between the mean values appear to be due to the presence of one or two outliers. When these outliers were removed from the data set, there was good agreement (Table 4-41).

Table 4-41. Mean concentrations (μg/L) of organic contaminants in samples collected at Hanscom AFB.

	Mean Concentration		Revised Mean Conc.	
Analyte	**DP**	**HS**	**DP**	**HS**
Benzene	1.2	1.6		
cis-1,2-Dichloroethylene	1.9	2.2		
Ethylbenzene	1.0	2.9		
p-Dichlorobenzene	2.7	2.6		
Trichloroethylene	62	91		

Toluene	88	2.1	1.7	2.1
o-Xylene	1.7	1.8		
Vinyl chloride	233	70	86	44

Table 4-42. Summary of statistical analyses of organic data for Hanscom AFB.

Analyte	N	Sign.of Well Type	Type of test	P= Prob.	Power of test
Benzene	17	NS	Paired *t*-test on log data	0.613	0.05
c-DCE	25	NS	Paired *t* -test on log data	0.121	0.214
Ethylbenzene	17	NS	Paired *t* -test on log data	0.546	0.05
o-Xylene	21	NS	Paired *t* -test on log data	0.353	0.05
p-DCB	28	NS	Paired *t* -test on log data	0.873	0.05
TCE	25	NS	Paired *t* -test on log data	0.793	0.05
Toluene	17	NS	Paired *t* -test on log data	0.44	0.05
Vinyl chloride	16	NS	Paired *t* -test on log data	0.493	0.05

Summary

The results of the statistical analyses of the data from this site indicated that there was no apparent bias that could be associated with using direct-push monitoring wells. The DP wells used at this site had no pre-pack filter and thus relied upon the natural formation to form a filter pack. In spite of the lack of a pre-pack filter, inorganic analytes, purge parameters, and organic contaminants did not appear to be affected by well construction method.

Tyndall Results:

For Phase I, there were eight clusters of wells. Each cluster contained four well types. Each cluster contained a 2-inch diameter HSA well with a conventionally designed filter pack, 1.5-inch diameter direct-push (DP) well with no filter, and a 1-inch diameter and a ½-inch diameter DP well with a pre-pack filter. The one exception to this was that the HSA well at cluster T-6 was 4 inches in diameter. The screen lengths were the same within a cluster but varied from well cluster to well cluster. Five clusters of wells had wells with approximately 10-foot screens (Cluster numbers 1, 2, 5, 8, 9). Among the other well clusters, one well cluster had approximately 15-foot well screens (Cluster T-6) and the other two well clusters had approximately 25-foot screens (Clusters D-9 and D-11).

For Phase II, two additional (replicate) wells were added to Cluster 9 and Cluster T-6. Each cluster received a duplicate 2-inch diameter HSA well and a duplicate 1.5-inch diameter DP well with no filter pack. Thus, for Phase II, there were six well clusters that contained the original four well types and two clusters that contained six well types.

Statistical analyses were used to compare the (Phase I and II) data from the four original well types. Separate statistical analyses were also conducted on the Phase II data to compare the six well types, including the original and replicate HSA wells and the original and replicate 1.5-in DP wells (with no pre-pack filter). Because this data set was considerably smaller, these analyses were less rigorous than those for the four wells.

Field parameter data

The five field parameters measured at this site were temperature, pH, turbidity, specific conductivity, and dissolved oxygen (DO). Table 4-43 presents the mean values for the four well types found in Phases I and II. Statistical analyses revealed that there were no statistically significant differences between any of the DP wells and the conventional HSA well for any of the purge parameters (Table 4-44).

Table 4-43. Mean values for field parameters measured at Tyndall AFB.

Parameter	Old HS	0.5-in. DP	1.5-in. DP	1-in. DP
DO (mg/L)	3.4	3.4	3.3	3.5
ORP (mV)	-8.5	-8.5	-34.9	-28.6
pH	5.6	5.5	5.6	5.7
Spec. Conductance (µS)	222	281 (213*)	195	290 (226**)
Temperature (°C)	26.1	26.1	25.8	26.1
Turbidity (NTU)	16.7	19.5	17.8	20.7

* Mean value minus 2 outliers.

** Mean value minus one outlier.

Table 4-44. Summary of statistical analyses for Tyndall AFB field parameter data comparing four well types.

Parameter	N	Sig. Dif.?	Type of test	Prob.	Power	Sig. dif. with HS well? 1.5-in. DP	1-in. DP	0.5-in. DP
DO	120	Yes/**No**	Friedman RM-ANOVA	0.044		No	No	No
ORP	120	**No**	Friedman RM-ANOVA	0.086				
pH	120	Yes/**No**	Friedman RM-ANOVA	0.047		No	No	No
Spec. Conductance	56	Yes/**No**	Friedman RM-ANOVA	0.030		No	No	No
Temperature	120	**No**	Friedman RM-ANOVA	0.256				
Turbidity	118	**No**	RM-ANOVA	0.062	0.377			

When the six well types were compared (i.e., the original and new replicate wells), no statistically significant difference was found between the new and original HSA wells or between the new and original 1.5-inch DP wells (Table 4-45 and Table 4-46).

Table 4-45. Mean values of the purge parameters for the six well types at Tyndall AFB.

Parameter	Old HS	0.5-in. DP	1.5-in. DP	New 1.5-in. DP	1-in. DP	New 2-in HS
DO (mg/L)	5.3	5.2	4.6	4.1	5	4.9
ORP (mV)	-50	-26	-37	-66	-51	-47
pH	6	**5.5***	**5.5***	5.6	6	5.8
Spec. Cond. (μS)	14405	22975	13162	981	10126	14440
minus outliers	776	446	520	981	632	463
Temperature (°C)	25.4	24.7	24.9	25.5	25.1	25
Turbidity (NTU)	12	9	20	32	10	11

* Significantly different from original HS well.
**Significantly different from new 2-in. HS well.

Table 4-46. Summary of statistical analyses for purge parameter data comparing six well types at Tyndall AFB.

Parameter	N	Sig. Dif.?	Type of test	Prob.	Power	Sig. dif. with HS well? New 2-in. HS	1.5-in. DP	New 1.5-in. DP	1-in. DP	0.5-in. DP
DO	19	No	Friedman RM-ANOVA	0.444						
ORP	21	No	RM-ANOVA on raw data	0.518	0.05					
pH	20	**Yes**	RM-ANOVA on raw data	<0.001	0.954	No	**Yes**	No	No	**Yes**
Spec. Cond.	21	Yes/ No	Friedman RM-ANOVA	0.027		No	No	No	No	No
Temp.	20	No	Friedman RM-ANOVA	0.772						
Turbidity	12	No	Friedman RM-ANOVA	0.161						

Inorganic analytes

The 15 inorganic parameters measured during Phase I included: alkalinity (to pH 4.5), barium, boron, calcium, chloride, iron, magnesium, manganese, nitrate, potassium, sodium, sulfate, total dissolved solids (TDS), total hardness, and zinc. Table 4-47 provides the mean values for each well type for each of the analytes. Statistical analyses revealed that there were no statistically significant differences between the three DP well types relative to the conventional HSA wells for almost all of the analytes (13/15) (Table 4-48). The two analytes where there were statistically significant differences between the DP wells relative to the conventional wells were manganese and sulfate. Manganese concentrations were significantly higher in the 1-inch diameter DP wells with a pre-pack filter, and the sulfate concentrations were significantly lower in the 1.5-inch diameter DP wells with no filter pack.

Table 4-47. Mean concentration of inorganic analytes in Tyndall AFB wells.

	Mean concentration (mg/L unless otherwise specified) Old HS (2-in.)	0.5-in. DP	1.5-in. DP	1-in. DP
TDS	126	120	114	130
Total Hardness	68	63	57	68
Alkalinity	50	43	44	52
Barium	16	16	15	16
Boron	0.89	0.84	0.92	0.91
Calcium	17	15	14	18
Chloride	9.8	9.5	10.2	9.8
Iron	0.63	0.71	0.60	0.74
Magnesium	1.8	1.6	1.4	1.8
Manganese	0.05	0.17	0.05	**0.16***
Nitrate	1.3	1.3	0.6	1.0

Potassium	7.8	7.6	7.8	7.8
Sodium	6.0	5.8	6.0	6.2
Sulfate	16	14	**13***	16
Zinc	9	16	10	37 (12**)

* Significantly different from HSA well.
** Mean concentration minus one outlier.

Table 4-48. Results of statistical analyses of inorganic data at Tyndall AFB.

Analyte	# of wells compared	N	Sig. Dif. w/ HS well?*	Type of test	Probability
Alkalinity	4	28	No	Friedman RM-ANOVA on ranks	0.377
Barium	4	24	No	Friedman RM-ANOVA on ranks	0.262
	6	6	No	Friedman RM-ANOVA on ranks	0.615
Boron	4	32	No	Friedman RM-ANOVA on ranks	0.871
Calcium	**4**	32	No	Friedman RM-ANOVA on ranks	0.031
Chloride	4	32	No	Friedman RM-ANOVA on ranks	0.369
Hardness (total)	4	24	No	Friedman RM-ANOVA on ranks	0.347
Iron	4	53	No	Friedman RM-ANOVA on ranks	0.009
	6	7	No	Friedman RM-ANOVA on ranks	0.191
Magnesium	4	32	No	Friedman RM-ANOVA on ranks	0.2
Manganese	4	55	**Yes**	Friedman RM-ANOVA on ranks	< 0.001
	6	7	No	One-way RM-ANOVA	0.148
Nitrate	4	15	No	Friedman RM-ANOVA on ranks	0.288
Potassium	4	32	No	Friedman RM-ANOVA on ranks	0.472
Sodium	4	32	No	Friedman RM-ANOVA on ranks	0.801
Sulfate	4	32	**Yes**	Friedman RM-ANOVA on ranks	0.005
Total Dissolved Solids	4	32	No	Friedman RM-ANOVA on ranks	0.174
Zinc	4	8	No	One-way RM-ANOVA on log data	0.697

For Phase II, samples were analyzed for a number of metals known to leach from stainless steel including Ba, Cd, Cr, Cu, Fe, Pb, Mn, Mo, and Ni. Concentrations of Cd, Cr, Cu, Mo, and Ni were typically below the detection limit**.** However, for three analytes (Ba, Fe, Mn),

concentrations were sufficiently high enough to allow statistical analyses of the data for the six well types. For all three analytes, there were no statistically significant differences between any of the new or original wells, including no statistically significant differences between the new and original HSA wells (Table 4-48). Table 4-49 shows the mean concentrations for these metals.

Table 4-49. Mean concentrations in newly installed wells and older wells at Tyndall AFB.

	Mean Concentration (mg/L)					
	Original	*New*			*New*	
Analyte	**HSA**	**2-in. HSA**	**0.5-in. DP**	**1.5-in. DP**	**1.5-in. DP**	**1-in. DP**
Ba	17	12	20	20	22	26
Fe	0.35	0.27	0.27	0.22	0.29	0.23
Mn	0.027	0.021	0.027	0.023	0.018	0.021

Organic contaminants

Table 4-50 shows the mean values for the various organic contaminants found at Tyndall AFB. For 7 out of the 14 analytes found, there was no statistically significant difference between the concentrations in the DP wells and the HSA wells (Table 4-51). For the analytes where statistically significant differences were found, clearly the well type with the largest number of analytes where statistically significant differences were found was the 1.5-inch-diameter DP well with no filter pack. For this well type, there were five analytes (benzene, *p*-dichlorobenzene, *cis*-1,2-dichloroethylene, ethylbenzene and TCE) with statistically significant differences. In contrast, the ½-inch- and 1-inch-diameter DP wells with a pre-pack filter pack had statistically significant differences for only 2 or 3 of the 14 analytes, respectively.

Table 4-50. Mean concentrations in the wells at Tyndall AFB.

	Mean concentrations (µg/L)			
Analyte	**0.5-in. DP**	**1.5-in. DP**	**1-in. DP**	**2-in. HS**
Benzene	**170***	**247***	**203***	150
p-Dichlorobenzene	19	**57***	24	20
cis-1,2-Dichloroethylene	48	**60***	71	54
trans-1,2-Dichloroethylene	5.7	7.5	**12.2***	7.7
Ethylbenzene	**46***	59	39	36
MTBE	29	76	43	27
TCE	94	**414***	213	79
1,1,1-Trichloroethane	15	35	28	24
1,1,2-Trichloroethane	15	11	13	12
Toluene	4.8	33.3	17.6	5.1
Vinyl chloride	15	14	**23**	16
m- & *p*-Xylene	93	163	110	81
o-Xylene	31	414 (87[1])	50	34

[1] Mean value minus one outlier.

*Values were significantly different from values for 2-in.HSA well.

Table 4-51. Summary of statistical analyses of organic contaminants at Tyndall AFB.

Analyte	N	Type of test	Significant Difference?	1 ½-in. DP no-pack	1-in. DP pre-pack	½-in.DP pre-pack	Other Sign. Difs.?
Benzene	66	Friedman RM-ANOVA	Yes	Yes	Yes	Yes	
p-Dichlorobenzene	31	Friedman RM-ANOVA	Yes	Yes	No	No	
cis-1,2-Dichloroethylene	56	Friedman RM-ANOVA	Yes	Yes	No	No	1 ½-in DP vs. 1-in.DP
trans-1,2-dichloroethylene	21	Friedman RM-ANOVA	Yes	No	Yes	No	
Ethylbenzene	63	Friedman RM-ANOVA	Yes	Yes	No	Yes	
MTBE	12	RM-ANOVA on raw data	No				
Tetrachloroethylene	10	RM-ANOVA on log data	No				
Toluene	45	Friedman RM-ANOVA	No				
1,1,1-Trichloroethane	10	Friedman RM-ANOVA	No				
1,1,2-Trichloroethane	9	RM-ANOVA on log data	No				
Trichloroethylene	65	Friedman RM-ANOVA	Yes	Yes	No	No	1 ½-in. DP vs.½-in. DP
Vinyl chloride	27	Friedman RM-ANOVA	Yes	No	Yes	No	
m- & p-Xylene	41	Friedman RM-ANOVA	No				
o-Xylene	48	Friedman RM-ANOVA	No				

Results from 2-way RM-ANOVAs

Analyte	**Location?**	**Well type?**	**Interaction?**
Benzene	Yes	No	**Yes**
p-Dichlorobenzene	Yes	**Yes**	**Yes**
cis-1,2-Dichloroethylene	Yes	No	**Yes**
trans-1,2-Dichloroethylene	Yes	No	No
Ethylbenzene	No	**Yes**	**Yes**
Trichloroethylene	Yes	**Yes**	**Yes**
Vinyl chloride	Yes	No	No

Two-way RM-ANOVA analyses revealed that there was a statistically significant interaction between well location and well type for most of the analytes where statistically significant differences were found (Table 4-51). This means that the effect of well type varied from well cluster to well cluster. This can be readily seen by examining Table 4-52, which provides the mean concentrations for each well cluster and analyte. For approximately 65 percent of the analytes, statistically significant differences between the DP wells and the conventional HSA wells occurred in the clusters that had wells with longer screen lengths. Specifically, the Cluster D-11 wells had 25-foot screens, and the Cluster T-6 wells had 15-foot screens. Because of the large magnitude of the differences in these concentrations, the well construction logs for these wells were re-evaluated. We found that the two 1.5-inch-diameter DP wells in these clusters had screen elevations that were more than 1 foot higher than the HSA wells. This may partially explain the differences that were found. That is, spatial heterogeneity associated with the distribution of solute concentrations and differences in screen elevations may have attributed to differences in concentrations observed within these well types.

Table 4-52. Mean concentrations of organic analytes by for each well cluster (with three or more sampling events) at Tyndall AFB.

Benzene

	Mean concentrations (µg/L)			
Cluster #	**0.5" DP**	**1.5" DP**	**1" DP**	**2" HS**
1	5.9	**8.6***	3.6	4.5
2	512	377	**543***	349
9	265	388	326	373
9-D	1.8	**35.7***	8.4	1.5
11-D	14	**297***	**102***	15
T-6	**150***	**72***	106	105

* Significantly different from 2-inch HS well

PDCB

	Mean concentrations (µg/L)			
Cluster #	**0.5" DP**	**1.5" DP**	**1" DP**	**2" HS**
1	2.7	3.4	0.7	0.7
2	6.5	6.0	5.5	6.2
8	2.6	1.4	1.6	2.2
9	85	82	69	88
D-9	2.1	27 (6.0[1])	2.7	3.6
D-11	8.1	**227***	63.1	19.9
T-6	10.0	9.1	8.3	6.0

[1] mean value minus two outliers

CDCE

	Mean concentrations (µg/L)			
Cluster #	**0.5" DP**	**1.5" DP**	**1" DP**	**2" HS**
1	19	**34***	13	17
2	61	49	39	44
5	**11***	**15***	7.0	4.3
8	106	116	226	141
T-6	10.2	5.9	9.6	9.3

TCE

	Mean concentrations (µg/L)			
Cluster #	**0.5" DP**	**1.5" DP**	**1" DP**	**2" HS**
1	19	**48***	9	16
5	438	**2134***	1028	320
8	**17***	**8.4***	79	63
9	18	35	34	27
D-9	1.4	5.5	1.3	0.8
D-11	0.4	**39***	**12***	2.1
T-6	35	22	26	24

Ethylbenzene

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
2	**16***	10	13	12
9	138	122	61	123
D-9	4.6	**37***	18	3.9
D-11	5.1	**104***	**51***	7.2
T-6	**104***	65	72	68

TDCE

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
1	9.5	9.7	4.9	4.9
5	3.7	9.4	3.3	1.2
8	5.9	7.4	18.7	11.5

No significant differences with 2-inch HS wells

* For all clusters with data for more than one sampling event

m,p-xylene

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
2	76	54	**92***	61
9	343	353	287	321
D-9	3.1	**25.3***	6.8	1.8
D-11	0.9	**282***	65	17
T-6	28	22	25	16

Toluene

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
2	5.7	3.5	5.4	3.7
9	7.3	18.1	6.7	16.1
D-9	2.6	6.7	1.7	1.5
D-11	1.8	**139***	**66***	2.0
T-6	7.1	4.7	8.0	4.6

MTBE

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
9	87	98	129	75
D-11	0.40	185	24	9.4
T-6	25	19	16	21

Not enough data to conduct statistical analyses

o-Xylene

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
1	1.0	1.2	0.7	0.6
2	29	25	33	23
9	114	106	75	109
D-9	4.1	1995 (23[1])	1.4	4.4
D-11	8.2	**296***	**150***	40
T-6	5.0	4.9	5.2	3.5

[1] minus one outlier

1,1,1-trichloroethane

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
9	7.3	42	47	38
T-6	**31***	22	21	23

1,1,2-trichloroethane

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
9	4.9	13	14	11
T-6	**28***	12	14	17

	Mean concentrations (µg/L)			
Cluster #	0.5" DP	1.5" DP	1" DP	2" HS
1	0.63	1.12	0.91	0.77
2	64	56	107	68
9	4.0	10.5	13.2	9.5
T-6	13.5	7.5	12.7	10.8

No significant difference with 2-in HS wells

Large differences between the concentrations in the 1.5-inch DP wells and the conventional HSA wells were also associated with other clusters with respect to TCE, Benzene, and *cis*-1,2-DCE. The presence of NAPL could also account for the observation that the 1.5-inch DP well consistently exhibited statistically significantly higher solute concentrations. Similar to the concept described above, whereby screens may not have intersected similar strata, it is possible that if NAPL is in the vicinity of the clusters, solute emanating from dissolution would migrate preferentially, impacting concentrations in wells within a given cluster with varying degrees based on their location relative to the preferential migration pattern. Perhaps the 1.5-inch well is located within the path of solute movement. Figure 4-10 displays a simplified configuration of this concept. For instance, DNAPL can lead to spatially heterogeneous solute concentration observations that depend upon well location relative to the solute plume configuration. Provided the groundwater gradient and direction remain relatively constant, the transect of concentration profiles shows that wells immediately downgradient of the NAPL source and within the solute pathway should consistently exhibit higher concentrations than wells located off center of the pathway (Figure 4-10). While solute concentrations did not reach effective solubilities, long screens could serve to dilute the values to levels below those commonly observed when NAPL is present. Even so, TCE concentrations seen here (in the hundreds of ppb) warrant concern about potential NAPL presence. Site personnel documented the potential for NAPL based on historical field observations (Tim McHale, personal communication, 2006).

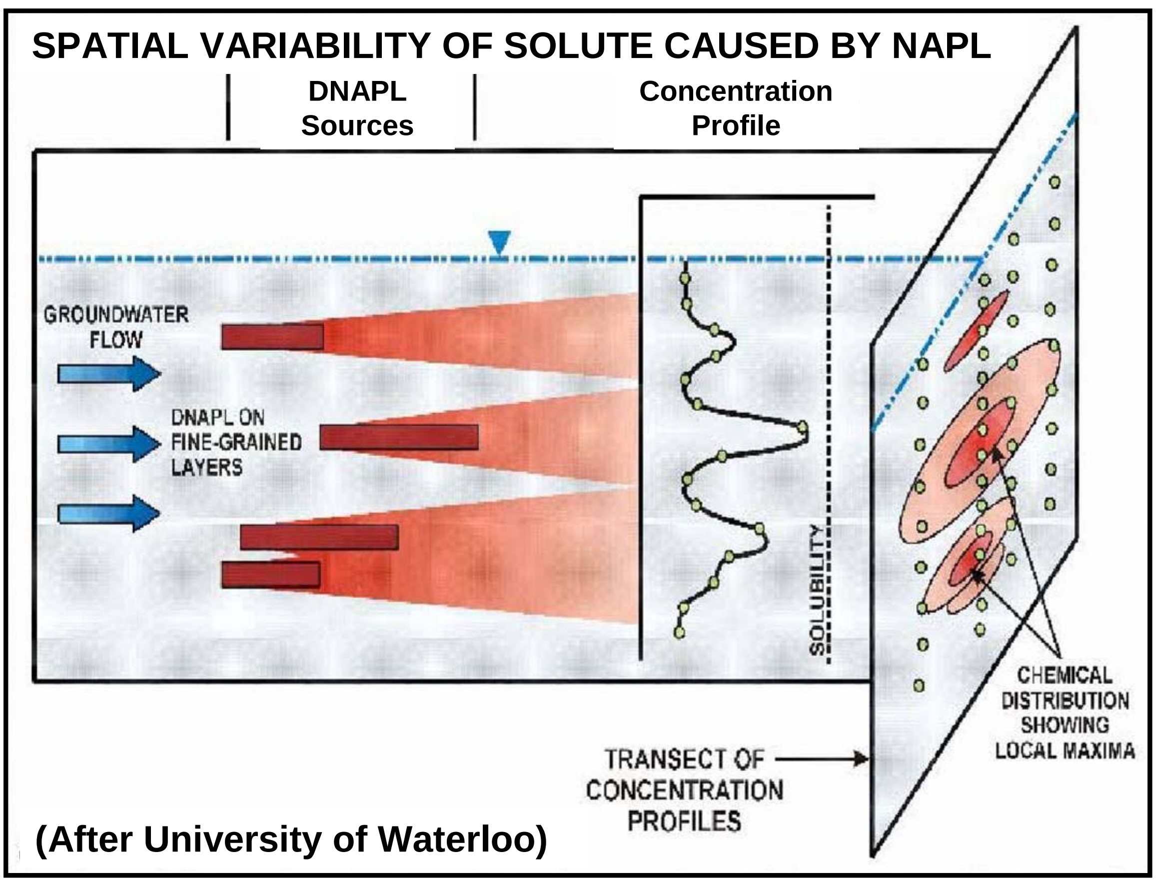


Figure 4-10. Spatial Variability of Solute Caused by NAPL.

There were only two analytes that were present in high enough concentrations to allow statistical comparison of the data from the new and original wells (i.e., all six wells), benzene and ethylbenzene. These analyses revealed that there was no statistically significant difference between the mean concentrations in the new and original HS well or between the new and original 1.5-inch DP wells (with no filter pack) (Table 4-53).

Table 4-53. Summary of the statistical analyses of six well types (including replicate wells) at Tyndall AFB.

				Significant difference from 2-inch HS				
Analyte	**N**	**Type of test**	**Sig.?**	***New* 2-in. HS**	**1.5-in. DP no-pack**	***New* 1.5-in. DP no-pack**	**1-in. DP pre-pack**	**1/2-in.DP pre-pack**
Benzene	12	Friedman RM-ANOVA	**Yes**	No	No	No	No	**Yes**
Ethylbenzene	11	Friedman RM-ANOVA	**Yes**	No	No	No	No	**Yes**
Toluene	6	RM-ANOVA on logs	No					

At this site, many of the VOC concentrations in these wells were at or near the detection limit. So, Pearson's Chi-square tests were conducted on the VOC data to determine the agreement between control (HSA) wells and each of the three differently designed DP wells at these low levels (i.e., to test the agreement between detect and non-detect data for each DP well type and the conventional HSA wells). Results of these tests are presented in Tables 4-54, 4-55, and 4-56. In all cases, the null hypotheses that the outcomes for the paired wells were unrelated were rejected, with very low P values of 0.001 or less. This means that there was good agreement between the concentrations in the DP wells and those in the conventional HSA wells. For the 1.5-inch no-pack DP wells, the percentage of matching outcomes over all compounds was 90.9 percent, which is substantially greater than the 62.2 percent that would be expected by chance if the two well types were independent of each other. For the 1-inch pre-pack DP test wells, the percentage of matches was 93.0 percent compared to the chance percentage of 63.3 percent. The percentage of matches for the 0.5-inch pre-pack DP wells was the lowest at 88.5 percent, but this still is substantially greater than the 63.4 percent of matches that would be expected by chance.

Table 4-54. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA control wells vs. 1.5-inch no-pack DP wells at Tyndall AFB.

Compound	**Sample Pairs**	**Control Well Detects**	**Number of Mismatches**		**Pearson's Chi-Square Test**	
			Control=D Test=ND	Control=ND Test=D	Chi-Square	Probability
1,1,1-trichloroethane	104	10	2	4	43.7	0.0000
1,1,2-trichloroethane	104	9	0	3	66.3	0.0000

1,4-Dichlorobenzene	98	27	3	7	52.9	0.0000
Benzene	104	55	0	11	63.9	0.0000
cis-1,2-Dichloroethene	104	50	5	6	61.5	0.0000
Ethylbenzene	104	56	4	8	58.4	0.0000
MTBE	88	12	2	3	45.8	0.0000
Tetrachloroethene	104	8	1	5	41.3	0.0000
Toluene	104	39	3	10	55.4	0.0000
trans-1,2-Dichloroethene	104	17	5	6	36.0	0.0000
Trichloroethene	104	60	6	4	64.1	0.0000
Vinyl Chloride	104	24	1	6	67.3	0.0000
Xylene (m,p)	72	32	0	10	38.1	0.0000
Xylene (o)	84	40	0	11	46.3	0.0000

Table 4-55. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA wells vs. 1-inch pre-pack DP wells at Tyndall AFB.

Compound	**Sample Pairs**	**Control Well Detects**	**Number of Mismatches**		**Pearson's Chi-Square Test**	
			Control=D Test=ND	Control=ND Test=D	Chi-Square	Probability
1,1,1-trichloroethane	104	10	2	3	48.5	0.0000
1,1,2-trichloroethane	104	9	3	1	46.4	0.0000
1,4-Dichlorobenzene	98	27	4	2	65.6	0.0000
Benzene	104	55	2	10	59.5	0.0000
cis-1,2-Dichloroethene	104	50	3	7	65.1	0.0000
Ethylbenzene	104	56	4	7	61.4	0.0000
MTBE	88	12	2	2	50.7	0.0000
Tetrachloroethene	104	8	3	1	40.6	0.0000
Toluene	104	39	3	6	66.5	0.0000
trans-1,2-Dichloroethene	104	17	1	3	72.3	0.0000
Trichloroethene	104	60	7	4	61.2	0.0000
Vinyl Chloride	104	24	2	3	73.4	0.0000
Xylene (m,p)	72	32	0	5	51.0	0.0000
Xylene (o)	84	40	2	5	55.4	0.0000

Table 4-56. Results of Pearson's Chi-square tests of detect/non-detect matches for 2-inch HSA control wells vs. 0.5-inch pre-pack DP test wells at Tyndall AFB.

Compound	Sample Pairs	Control Well Detects	Number of Mismatches		Pearson's Chi-Square Test	
			Control=D Test=ND	Control=ND Test=D	Chi-Square	Probability
1,1,1-trichloroethane	102	10	4	1	40.2	0.0000
1,1,2-trichloroethane	102	9	3	1	45.4	0.0000
1,4-Dichlorobenzene	97	26	5	7	43.2	0.0000
Benzene	102	53	6	9	48.0	0.0000
cis-1,2-Dichloroethene	102	50	3	17	38.4	0.0000
Ethylbenzene	102	54	4	8	56.7	0.0000
MTBE	88	12	4	1	41.4	0.0000
Tetrachloroethene	102	8	1	3	50.1	0.0000
Toluene	102	38	7	4	56.7	0.0000
trans-1,2-Dichloroethene	102	17	7	11	15.5	0.0001
Trichloroethene	102	59	7	8	46.8	0.0000
Vinyl Chloride	102	23	5	5	48.7	0.0000
Xylene (m,p)	70	31	5	10	21.2	0.0000
Xylene (o)	81	38	2	8	44.1	0.0000

Summary

For the Tyndall purge parameters and inorganic analytes, there was generally good agreement between the values reported for the DP wells relative to the conventionally installed HSA wells and there does not appear to be any trend that is associated with well type. The same was true for the organic contaminants recovered from the 0.5-inch and 1-inch pre-pack DP wells (with quasi-static installation). However, for the 1.5-inch DP wells with no filter pack (with hammer installation), a number of statistically significant differences were found between the concentrations of organic contaminants in these wells relative to the conventional HSA wells, especially in wells with longer screens. It appears that for at least a few wells, screened zones do not overlap the same depth range as the control drilled well. In addition, it is suspected that NAPL could be present, leading to preferential flow patterns that would exhibit consistently higher solute concentration values in specific wells within the migration pathway.

Final Conclusions from the Statistical Analyses

The results of the statistical analyses of the data from all sites for the purge parameters, inorganic analytes, and the organic contaminants in samples collected from the pre-pack and no-pack DP wells are summarized in Tables 4-57 and 4-58.

Table 4-57. Summary of statistical analyses comparing pre-pack DP and HSA wells.

Pre-pack wells

Location	Well diameter	Well type	Ratio of analytes with no significant difference vs. total number of analytes		
			Purge parameters	Inorganic analytes	Organic analytes
CRREL	1/2 inch		3/5	2/2	1/1
	3/4 inch		1/5	2/2	0/1
Dover	3/4 inch		4/6	3/3	5/5
Tyndall	1/2 inch		6/6	15/15	11/13
	1 inch		6/6	14/15	10/13
Hueneme	3/4 inch	ASTM	3/6	13/13	1/1
	3/4 inch	Conv. filter	5/6	15/16	1/1
	2 inches	ASTM	6/6	10/13	1/1
Total			34/46	74/79	30/36
			74%	94%	83%

Table 4-58. Summary of statistical analyses comparing no-pack DP wells and HSA wells.

No-pack wells

Location	Well diameter	Ratio of analytes with no significant difference vs. total number analytes		
		Purge parameters	Inorganic analytes	Organic analytes
Dover	3/4 inch	2/5	2/3	5/5
	2 inches	5/6	12/15	10/14
Hanscom	2 inches	5/6	9/10	8/8
Tyndall	1 1/2 inches	6/6	14/15	9/13
Hueneme	3/4 inch	4/6	14/16	1/1
Total		22/29	51/59	33/41
		76%	86%	80%

Final Conclusions from Statistical Analyses of Organic Contaminant Data:

With respect to the results of the statistical analyses of the data containing the organic analytes, observations to note include the following.

- For most of the analytes and test sites, there does not appear to be a systematic bias than can be associated with DP well construction, including no-pack DP wells and DP wells of different diameters.

- For the VOC concentrations in the pre-pack DP wells, there was excellent agreement with the conventional wells at Dover AFB and at Port Hueneme. The sites where agreement was the poorest included Tyndall AFB and CRREL.

- At CRREL, differences between the mean organic analyte concentrations for the two DP well types and the HSA wells were not consistent from well cluster to well cluster. For one of the ¾-inch DP wells at CRREL, there were large differences in the mean TCE concentrations and in the mean Specific Conductance values when compared with the HSA well. These data suggest that a slightly different part of the formation was sampled. Given the fact that pure product was accidentally released into fractured bedrock from a deep refrigerated well that was used by laboratory engineers to test ice augers just below the deep well, consistent differences are suspected to be due to well proximity to NAPL that is dissolving and migrating into the sampling capture zone.

- For the few analytes where statistically significant differences were found between the pre-pack DP wells and the HSA wells, the differences were not large in magnitude and would not have impacted any management decision.

- The percent agreement between the no-pack DP wells and the HSA wells was essentially the same as that observed for the pre-pack DP wells.

- For the no-pack DP wells, there was excellent agreement (100 percent) between the ¾-inch DP wells and the HSA Wells at Dover and Port Hueneme and between the 2-inch DP wells and the HSA wells at Hanscom. The poorest agreement was observed for the 2-inch no-pack DP wells at Dover and the 1.5-inch no-pack DP wells at Tyndall. These differences are suspected to be due to proximity to NAPL.

- For the no-pack DP wells at Dover, the effect of well type was not consistent from well cluster to well cluster.

- For several analytes at Tyndall AFB, large differences were observed between the mean concentrations for the no-pack DP wells and the HSA wells. Historical observations suggest that NAPL may contribute to spatial variabilities.

- Higher-level ANOVA tests conducted on the Port Hueneme MTBE data revealed that any systematic differences associated with well design were small relative to the temporal variations and were not statistically significant. Temporal variations associated with DP wells agreed with those observed in the conventional wells.

- Correlation analyses conducted on the Port Hueneme MTBE data revealed that there were statistically significant correlations between the concentrations in the DP wells and those in the conventional HSA wells for all four of the DP well types at this site (including no-pack DP wells).

- Because much of the VOC data from Dover AFB and Tyndall AFB was near, at, or below the detection limit, statistical analyses (Pearson’s Chi-square tests) were conducted

to determine if there was agreement between detect vs. non-detect data for each of the DP well types. These analyses revealed that even at low analyte concentrations, there was no significant difference between the performance of any of the DP well types and the HSA wells at either site.

- There also were no statistically significant differences observed between VOC concentrations in the replicate HSA wells and the original HSA wells or between the replicate and original DP wells. In fact, spatial variabilities are demonstrated by the observation that for some sampling events, all the experimental well concentrations fall within the range of concentrations between the control drilled well and duplicate well.

Final Conclusions from Statistical Analyses of Inorganic Analyte Data:

With respect to the analyses of the inorganic analytes, observations to note include the following.

- For most of the analytes and test sites, there does not appear to be a systematic bias that can be associated with DP well construction.

- The percent agreement between concentrations of inorganic analytes in samples from pre-pack DP wells relative to those in samples from conventional HSA wells appears to be slightly better than that achieved with the no-pack DP wells.

- In the few instances where statistically significant differences were found, the differences generally were not large in magnitude and most likely would not have impacted any management decision.

- Generally there were not any statistically significant differences between inorganic analyte concentrations in the replicate and original HSA wells. The one exception was at Dover AFB for Mn concentrations where differences were attributed to spatial heterogeneity at the site.

- Based upon the data from Phase II, leaching of metal constituents from the stainless steel components of the pre-pack DP filter packs was not a concern during this study.

Final Conclusions from Statistical Analyses of Purge Parameter Data:

With respect to the purge parameter data, key observations include the following:

- The percentage of purge parameters for which there was no statistically significant difference between DP and HSA wells was much less than the percentage for the VOCs and inorganic analytes. This was especially true for the pre-pack DP wells.
- The percent agreement between the pre-pack DP wells and the HSA wells and between the no-pack DP wells and the HSA wells was essentially the same.
- At three sites there was good agreement between the purge parameters measured in samples collected from the DP and HSA wells. The exceptions were the wells at CRREL and Port Hueneme.

- The purge parameters where there was the poorest agreement between the DP and HSA wells included turbidity and Dissolved Oxygen.

- For those sites where there were statistically significant differences between the DP and conventional wells for turbidity, there was no consistent bias that could be associated with DP well construction, including well diameter, or the presence or absence of pre-pack filters.

- For those sites where there was a significant difference between the Dissolved Oxygen content of the samples from the DP wells vs. the conventional wells, there was no consistent bias that could be associated with the presence or absence of a pre-pack filter.

- Generally, there were no significant differences between the purge parameters measured in the original HSA wells relative to the replicate HSA wells, or between the original DP wells relative to the replicate DP wells.

It is not surprising that the agreement for the purge parameters is not as good as it was for the inorganic and organic analytes. For one, significantly less stringent QA/QC procedures are used in the calibration and maintenance of purge monitoring equipment in the field when compared to the procedures used for laboratory analyses. Also, the final values recorded may not have represented a stable reading in all cases, and differences in the residence time of groundwater in the sampling tubing could have influenced the temperature, ORP, and DO. With continued pumping for sampling, one would expect that these differences would be less of a concern.

Key Conclusions:
- For the majority of the comparisons conducted during this demonstration project, management decisions would not be impacted regardless of whether the well is installed by drilled or direct-push methods.
- DP wells perform comparably to drilled wells with respect to organic solute concentration measurements, inorganic concentration measurements, and hydraulic assessment capabilities.
- For LTM applications, DP wells are capable of providing representative chemical and water level information.
- All sites included in our demonstration had both conventional drilled wells as well as direct-push wells. Our primary conclusion is that the chemical concentration results were virtually identical given that the majority of the variability was due to spatial and temporal factors—not well type—and therefore we generally advocate the use of commingled data from both conventional and direct-push wells as appropriate for LTM applications.

4.3.2 Hydraulic Comparisons

Hydraulic comparisons were conducted at Port Hueneme Cluster B (Bartlett *et al.*, 2004). A complete report is presented as Appendix B. The main objectives of this research were:

- to perform a systematic comparison of hydraulic conductivity values derived from conventional and DP wells;
- to evaluate the validity of conducting short duration pneumatic slug tests in high permeable formations; and

- to help develop guidance on well construction and test methods for improving the determination of hydraulic conductivity values from well testing.

To meet these objectives a study was performed from March 9 to 20, 2003 at a pre-existing test site at the Naval Base Ventura County, Port Hueneme, California. Over 296 pneumatic slug-in and slug-out tests as well as multiple steady and unsteady state pumping tests were performed in 5 different wells types in 15 different wells. The 5 different well types included: 2 inch diameter conventional hollow stem auger wells, 2 inch diameter DP wells with pre-packs, two ¾ inch pre-pack DP wells with different types of pre-pack designs, and ¾ inch naturally developed pre-pack wells. The wells were screened between 7 and 17.5 feet in fluvial-deltaic sediments consisting of medium to coarse-grained sand and gravel. The groundwater table was relatively shallow from 5 to 7 feet deep and all the screens were fully submerged.

The pertinent conclusions of the study were:

- Short duration pneumatic slug tests were determined to be a viable approach for determining hydraulic conductivity values in a high permeable formation. The results of a statistical comparison between the pneumatic slug tests lasting only a few seconds and the steady state pumping tests yielded no statistical difference.
- Hydraulic conductivity values in DP wells were found to be independent of pre-pack design, well radius, induced head, and test method (assuming the same screened interval).
- The hydraulic conductivity values determined from the different well types in the B1 and B2 clusters had a mean post development value of 2 b 10^{-2} cm/sec and a standard deviation of 8 by 10^{-3}. The ANOVA analysis indicated there was no statistical difference amongst the pre-pack wells. Furthermore, there was no statistical difference between the pushed no-pack wells and the drilled wells. However, the ANOVA analysis indicated that there was a statistical difference between the latter wells and the pre-pack wells. The variance associated with hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells are largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method.
- Although development had an impact on the hydraulic conductivity for most of the wells, the impact was ambiguous. Of the 15 wells tested, 10 wells had statistical differences in hydraulic conductivity between pre and post development. Of the 10 wells, 5 wells showed increases in hydraulic conductivities and 5 well showed decreases.
- Unsteady state, steady state pump tests, and pneumatic slug tests were shown to be statistically comparable means of determining hydraulic conductivity analysis in high permeable formations.

The following is additional guidance to improve pneumatic slug testing in high permeable environments.

- Three or more tests should be done at any given well to determine reproducibility;
- Attention should be paid to proper well design (especially having the screened section fully submerged during testing) and rigorous well development;
- Care must be taken in choosing the appropriate portion of the log head versus time curve for analysis;

- High frequency data acquisition pressure transducers should be used in conducting tests in highly permeable wells;
- Use of vacuum-pressure pumps permits conducting slug-in, in addition to slug-out tests in a very controlled, highly reproducible manner; and
- Spreadsheet templates should be developed to aid in data management and analysis.

Based on the results of this study, the following are recommendations for future research to improve slug test methods and to evaluate differences in hydraulic conductivities determined in different well types:

- Ideally the comparative tests conducted here would have been enhanced if there were more well clusters all screened over the same depth interval. This would help reduce ambiguities, increase the data for statistical analysis, and permit an assessment of the degree of spatial heterogeneity by examining how the hydraulic conductivities vary for a given well type.
- *It would also be valuable to have wells developed and tested immediately following installation.*
- To examine the impact of scale on the determination of the hydraulic conductivity value, two well steady state pumping tests should be conducted. For example, using one well as the pumping well and having multiple observation wells at different distances, one can evaluate how the hydraulic conductivity varies spatially and with distance for comparison to the slug test results.
- It would be useful to conduct testing at several locations having widely different hydraulic conductivities. These tests would help evaluate the extent to which hydraulic conductivity values determined in wells in different formation types are sensitive to well installation and development.

5.0 COST ASSESSMENT

5.1 Cost Reporting

Actual demonstration-related well installation costs varied for each site. This was in part due to the fact that previously installed wells at some sites, such as Hanscom, were used to leverage project costs. For these cases, existing wells were paired or clustered with new wells for comparison tests. For other sites, such as the Port Hueneme facility, a location was selected to specifically compare conventional drilled wells to direct-push wells. For the Hueneme test site, several site characterization steps were conducted prior to test cell design and well installation as part of the experimental design to limit variability and influence from external factors such as heterogeneous soil type distributions. For instance, piezocone pushes were advanced to identify candidate screen zones within the cells, soil cores were collected and analyzed to target high permeability zones for well screen depth ranges which emphasized advective flux (versus diffusive flux), and grain size distributions were conducted to determine well design constraints in accordance with ASTM D5098. While this is the preferred approach to designing monitoring wells, contractors rarely follow these steps during production-oriented efforts. Therefore, this cost assessment focuses on costs that practitioners would encounter for installations of drilled and direct-push wells. Since installation costs are typically dominated by an initial expenditure for time and materials, a net present value evaluation will not be developed. Furthermore, discounted variable cost components such as sampling and analyses are considered comparable for both conventional and DP wells. Therefore, the cost assessment will emphasize elements within the well installation process and focus on the key cost differences between the two installation approaches.

Table 5-1 presents cost tracking categories and details. Cost considerations included expenses for mobilization, materials, labor, waste generation, per diem, well development, reporting, production rates (also a cost driver based on associated labor requirements), well rehabilitation, and well removal and decommissioning. Many of the costs incurred for drilled wells also apply for DP wells (e.g., surveying, certain material costs, etc.). The potential savings afforded by DP wells is typically dominated by the more rapid rate of installation, associated lower accrued labor expenses, and lower waste handling costs. Given a one-to-one comparison between drilled and DP well costs, the efficiencies of the DP well installation efforts lead to significant savings, especially when using smaller diameter DP wells. However, not included in this comparison is the critical fact that DP well installations can be part of a sequence of expedited direct-push field activities conducted during a single deployment. For instance, use of a laser induced fluorescence (LIF) probe for plume delineation, followed by a high-resolution piezocone for detailed three-dimensional modeling, can then be followed by customized DP well installations (based on the Kram and Farrar method) at optimized locations and depth ranges for long-term monitoring purposes. In contrast, drilled wells are typically not part of a Triad-based field analytical sequence, but are more commonly installed independently as a single deployment to serve as an intermediate step between field screening and long-term monitoring strategies.

Table 5-1. Cost Tracking.

COST CATEGORY	SUB CATEGORY	DETAILS
START-UP COSTS	Site Characterization	Typically preliminary, but could be detailed
	Mobilization	Planning, contracting, personnel mobilization, transportation, permitting, site preparation
OPERATING COSTS	Operator Labor	Time requirements
	Consumables, Supplies	Fuel, water, etc.
	Residual Waste Handling	Volume differentials
	Offsite Disposal	Based on volumes
	Waste Manifesting	Based on volumes
	Well Logging	Number per day
	Reporting	Time requirements
	Surveying	Time requirements
	Well Development	Time requirements, waste generation
	Demobilization	Equipment removal, site restoration, decontamination, personnel demobilization
	Rehabilitation	Time requirements, waste generation
	Well Removal	Time requirements, waste generation

Table 5-2 presents itemized cost assumptions used in the derivation of the cost comparisons for target depths of 20 feet, 50 feet, and 75 feet below grade. Baseline technology includes 2-inch diameter rotary installed wells. Specifically, hollow stem auger (HSA) drilled wells are installed via rotary methods. DP well cost assumptions are based on ¾-inch diameter and 2-inch diameter designs. For cost comparison purposes, all well screens are assumed to be 5-foot sections, and the examples are based on sets of 10 wells for each deployment set to the target depths specified. Many of the itemized costs are identical between DP wells and rotary wells. However, differences can arise when target depths, well diameters, and associated material costs are considered. The most significant differences contributing to DP well cost savings are due to the

rapid installation rates (which impact labor and per diem cost totals) and the low waste generation volume and management requirements.

Table 5-2. Itemized Cost Assumptions. Well screens are assumed to be 5-foot sections. Calculation examples are based on sets of 10 wells for each deployment set to the target depths specified. Hardware costs are based on quotes from 2004.

	20'		50'		75'	
	Direct-Push Wells	Drilled Wells	DP	Drilled	DP	Drilled
Well Diam.	2" and 3/4"	2"	2" and 3/4"	2"	2" and 3/4"	2"
Max Well Depth	20' (6.1m)	20' (6.1m)	50' (15.24m)	50' (15.24m)	75' (22.86m)	75' (22.86m)
Mobilization (10 wells)	$1,000	$1,000	$1,000	$1,000	$1,000	$1,000
Average No.	15	3	5	1	3	1
Installations/Day						
Riser Pipe Costs	$1.75/ft (3/4")	$1.77/ft	$1.75/ft (3/4")	$1.77/ft	$1.75/ft (3/4")	$1.77/ft
	$1.77/ft (2")		$1.77/ft (2")		$1.77/ft (2")	
Screen Costs	$2.85/ft (3/4")	$2.57/ft	$2.85/ft (3/4")	$2.57/ft	$2.85/ft (3/4")	$2.57/ft
	$2.57/ft (2")		$2.57/ft (2")		$2.57/ft (2")	
Filter Pack Costs	$10/ft (3/4")	$1.18/ft	$10/ft (3/4")	$1.18/ft	$10/ft (3/4")	$1.18/ft
	$28/ft (2")		$28/ft (2")		$28/ft (2")	
Solid Waste Generation*	0 drums	0.75 drums/well	0 drums	1.88 drums/well	0 drums	2.82 drums/well
Decon Rinseate Generated*	0.2 drum/well (3/4")	1 drum/well	0.5 drum/well (3/4")	2.5 drums/well	0.75 drum/well (3/4")	3.75 drums/well
	0.3 drum/well (2")		0.75 drum/well (2")		1.13 drum/well (2")	
Development Water Generated*	20 gal/well (3/4")	45 gal/well	50 gal/well (3/4")	112.5 gal/well	75 gal/well (3/4")	168.75 gal/well
	45 gal/well (2")		112.5 gal/well		168.75 gal/well	
Monument (flush)	$33 ea. (8" skirt)	$33 ea. (8" skirt)	$33 ea. (8" skirt)	$33 ea. (8" skirt)	$33 ea. (8" skirt)	$33 ea. (8" skirt)
Bottom cap	$4.87 (3/4")	$5.50	$4.87/ft (3/4")	$5.50	$4.87/ft (3/4")	$5.50
	$5.50 (2")		$5.50 (2")		$5.50 (2")	
Labor Rate	$1000/day	$1000/day	$1000/day	$1000/day	$1000/day	$1000/day
Per Diem ($100pp/day)	$200/day	$200/day	$200/day	$200/day	$200/day	$200/day
Grout	$15	$15	$135	$135	$210	$210
Foam Seal	$20 (3/4")	NA	$20 (3/4")	NA	$20 (3/4")	NA
	$30 (2")		$30 (2")		$30 (2")	
Survey (10 well)	$1,500	$1,500	$1,500	$1,500	$1,500	$1,500
Well Log	$200	$200	$200	$200	$200	$200
Well Development	$250 (3/4")	$500	$500 (3/4")	$1,000	$700 (3/4")	$1,500
	$500 (2")		$1000 (2")		$1500 (2")	
Reporting	$300	$300	$300	$300	$300	$300

Table 5-3. Itemized Well Rehabilitation and Removal Cost Assumptions. Calculation examples are based on sets of 10 wells for each deployment.

	20'		50'		75'	
	Direct-Push Wells	Drillled Wells	DP	Drilled	DP	Drilled
Labor Rates	$1000/day	$1000/day	$1000/day	$1000/day	$1000/day	$1000/day
Average No.	2	2	2	2	2	2
Labor Days						
Labor (Remove)	2000	2000	2000	2000	2000	2000
Per Diem (Remove)	1200	1200	1200	1200	1200	1200
Labor (Rehab)	4000	4000	8000	8000	10000	10000
Per Diem (Rehab)	1200	1200	1600	1600	2000	2000
Grouting	600	600	1200	1200	1800	1800
Grout Rig (Mob)	1000	1000	1000	1000	1000	1000
Solid Waste	500	500	1000	1000	1500	1500
Liquid Waste*	800	2000	800	2000	800	2000
Reporting	1000	1000	1000	1000	1000	1000
Totals 3/4	$12,300	-	$17,800	-	$21,300	-
Totals 2"	$13,500	$13,500	$19,000	$19,000	$22,500	$22,500

When considering Life-Cycle costs, sampling and monitoring costs for DP and drilled wells should be very similar regardless of well depths. As can be seen in Table 5-3, small differences arise when considering liquid wastes associated with well rehabilitation efforts. Liquid wastes refer to well development water.

5.2 Cost Analysis

The primary factors influencing costs associated with the installation of either DP or conventional wells are directly related to the generation of solid and liquid industrial derived wasted (IDW) and time considerations (Kram *et al.*, 2001). Time is a significant consideration, especially if one uses the Kram and Farrar Well Design Specification (WDS) approach for well design, as it saves over 50 percent of the installation time when compared to the sampling and grain size distribution via sieve analyses approach described and recommended in ASTM D5092. Furthermore, since one can install wells using CPT, well installations can be coupled to site characterization efforts, and well designs based on CPT soil classifications and WDS (which is based on ASTM grain size distributions) are optimized and therefore more cost effective, as there is a reduction in the location redundancies, each well location is based on specific data needs for that portion of the plume configuration, and probabilities for well failure are significantly reduced. Drilling spoils are essentially non-existent for DP wells, with the exception of a small amount of soil removed while installing the surface seal and traffic or "Christy" box. Conversely, conventional well installations typically generate a significant volume of soil cuttings. For example, during the installation of the conventional wells at the Port Hueneme site, approximately 40 gallons [5.35 ft^3] of IDW were generated for each conventional well installed to a depth of 20 feet [6.1m] bgs.

Costs are based on materials (e.g., riser pipe, screens, filter packs, bottom caps, traffic monuments, grout, sealing materials, etc.), depths (which impact hardware and labor costs), rates of installation for each approach (impacting total labor and per diem costs), waste generation, and labor costs (dependent upon installation rates, and survey, logging, development and reporting requirements). Many of the itemized costs are identical between DP wells and rotary wells. However, differences can arise when target depths, well diameters, and associated material costs are considered. The most significant differences contributing to DP well cost savings are due to the rapid installation rates (which impact labor and per diem cost totals) and the low waste generation volume and management requirements.

Life cycle costs for DP wells were evaluated relative to conventional drilled well costs. As demonstrated in Tables 5-2 and 5-3, installation costs for 10 wells comprised of 5-foot screens represent the largest component of life cycle cost differences between DP wells and drilled wells. Once the wells have been installed and developed, provided that low flow sampling methods are used, and that well removal costs are similar, post-installation and development DP and drilled well life cycle costs are anticipated to be identical. Modest exceptions would be rehabilitation cost differentials between ¾-inch DP wells and the 2-inch wells (both DP and drilled), and grouting costs based on depths and hole diameter.

Conservative cost savings are illustrated in Table 5-4 (modified from Kram *et al.*, 2003). Savings are derived based on total maximum well depth and well diameter. For each category, it was assumed that 10 wells were installed at each location and that all well screens were 5 feet

[1.52m] in length. Other considerations included costs for materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for DP well installations range from approximately 32 to 68 percent (Figure 5-1). Highest percentage savings can be derived when using smaller diameter wells at deeper total depths. Users must consider that smaller diameter wells may not be appropriate for some applications (e.g., when a pump is to be used), that deeper wells can be more challenging for DP installation methods, and success will depend upon the soil lithology and resistance to hydraulic or hammer installation techniques.

Table 5-4. Cost Comparison Between DP and Drilled Monitoring Well Installations. Estimates were derived assuming 10 wells per site, each designed with 5-foot [1.52m] screens.

Total Depth	Direct-Push Wells		Drilled Wells	3/4" Savings	2" Savings
	3/4"	2"	2"	3/4"	2"
20	$7,799	$10,254	$15,146	48.5%	32.3%
50	$10,664	$14,575	$28,418	62.5%	48.7%
75	$14,876	$20,543	$46,393	67.9%	55.7%

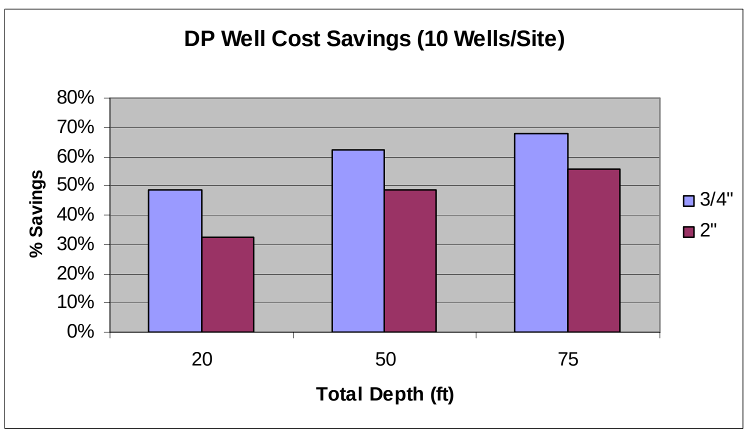


Figure 5-1. Percentage Savings for DP Well Installations Based on Well Diameter and Depth.

When accounting for the total DoD savings due to DP well installations versus conventional drilled wells, several assumptions were used. Since the number of DoD well installations per year is unknown, it was assumed that 500 wells per state are currently installed each year. The authors recognize that this value is not correct, and that it is perhaps overly conservative (e.g., actual number is probably much higher). For instance, at NBVC Port Hueneme alone, several hundred wells were installed per year for several years in a row. Regardless, Figure 5-2 displays the total anticipated DoD savings per year assuming 25,000 DP wells (or 500 per state) are

installed per year. Cost avoidance estimates range from approximately \$12M to close to \$80M per year for DoD alone. Since the majority of DP wells are less than 2 inches [5.08cm] in diameter, the low end DoD cost savings estimate is approximately \$20M per year. Using these conservative estimates, industry savings could exceed \$200M dollars per year with as few as 1,300 DP well installations per state per year.

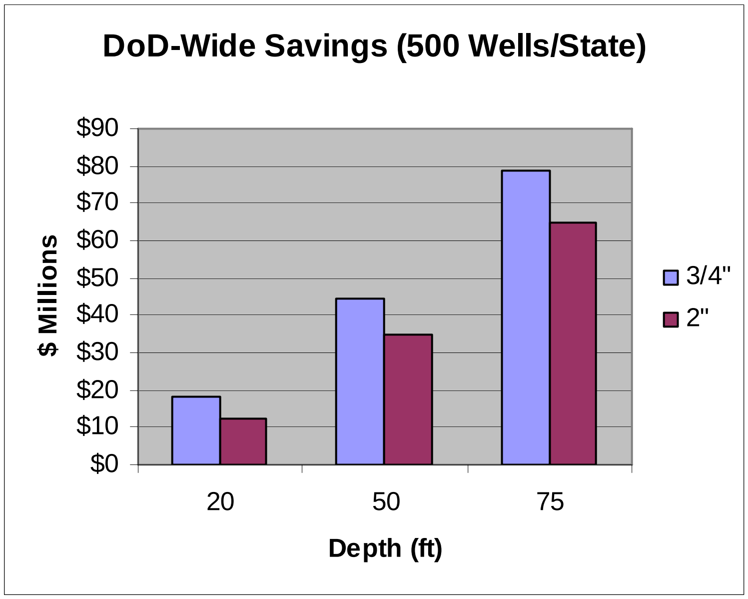


Figure 5-2. Anticipated DoD Annual Savings by DP Well Installations for LTM. Values were derived assuming that 500 DP well installations would be completed per state each year.

During the advisory committee workshop following Phase I of this demonstration, California regulators expressed concern about filter pack design in drilled wells. The primary issues have to deal with the fact that most DP wells are not designed in accordance with ASTM D5092, which requires sieve analyses to determine grain size distributions. Formation candidate screen zone grain size distributions dictate filter pack gradation and subsequently screen slot size. Interestingly, conventional wells are also required to meet these guidelines, yet rarely do installers follow these directives. Instead, in order to avoid the required sampling, sieve, and redeployment steps, drillers typically use a “one-size-fits-all” design that consists of a 20/40 sand pack tremmied to reside adjacent to a 0.010 inch [.03cm] slotted screen section. Silty sand and finer materials can readily pass through this configuration. As a result, well failure becomes possible, and often probable, especially in silt and clay rich formations.

To adequately address regulatory concerns regarding DP well design constraints, Kram and Farrar developed Well Design Specification (WDS) software, which allows the user to determine the appropriate filter pack gradation and slot size requirements based on cone penetrometer soil type descriptors (U.S. Patent 6,317,694). Well design specifications can be determined in real-time, effectively eliminating the need to collect a soil sample, reducing the time required in the

field, and allowing for well design and installation during a single deployment. WDS is currently available on the Navy SCAPS system, as it has been integrated into the WinOCPT data acquisition and processing package. When compared to conventional sampling and sieving approaches for proper well design, cost avoidance through use of WDS prior to DP well installation can be significant, often exceeding 50 percent savings. Primary savings drivers consist of reduction in field time and labor due to avoidance of need to collect samples, reduction in laboratory time due to avoidance of need to conduct sieve analyses, and reduction in need for additional remobilization step following laboratory results.
Assuming that well removal rates will be approximately 1.5 hours per well (for a total of 15 hours for a 10 well site) using the extraction method developed by Major and Osgood, life cycle costs for 10 wells at a given site are presented below (Table 5-5) for each of the three depths (i.e., 20 feet, 50 feet and 75 feet below grade). This table was developed assuming that one well rehabilitation/redevelopment effort was required, and that well removal costs are identical for each well type (2 days total for each scenario). Installation costs (Table 5-4) were added to rehabilitation and removal costs (see Table 5-3 for assumptions) to derive the values presented in Table 5-5. Since most drillers do not currently properly design wells following ASTM recommended practices (e.g., sieve analyses followed by filter pack and slot selections) these estimates do not include additional cost savings afforded by the Kram and Farrar WDS approach. Life cycle cost savings associated with DP wells is significant, ranging from approximately 17 to 47 percent, and tends to be highest for smaller diameter wells installed to deeper depths. Obviously, there are limitations to this generalization, as DP wells can be difficult to install to zones deeper than approximately 75 feet below grade unless formation conditions are ideal.

Table 5-5. Life-Cycle Cost Comparison Between DP and Drilled Monitoring Wells. Estimates were derived assuming costs for 10 wells per site, including installation, rehabilitation, and removal.

Total Depth	Direct-Push Wells		Drilled Wells	3/4" Savings	2" Savings
	3/4"	2"	2"	3/4"	2"
20	$20,099	$23,754	$28,646	29.8%	17.1%
50	$28,464	$33,575	$47,418	40.0%	29.2%
75	$36,176	$43,043	$68,893	47.5%	37.5%

It is important to note that the cost difference between DP and drilled wells would most likely be much greater when used in production mode (as opposed to a research effort or using the cost avoidance assumptions employed in this projection). For instance, the number of DP wells installed would be much higher for a conventional project (e.g., up to 15 DP wells per day in the same geologic setting) whereas the maximum number of HSA wells team members have installed is 4 per day at the same site. The difference in daily production rate would lead to greater economies of scale on a large remedial investigation (RI) project than are evident from this small demonstration study. Furthermore, when coupling the well installation efforts with other DP site characterization technologies such as plume delineation, cost benefits for DP wells are even more significant than those represented in this section.

5.3 Cost Comparison

Conservative cost savings are illustrated in Table 5-4 and Figure 5-1 (modified from Kram *et al*., 2003). Savings are derived based on total maximum well depth and well diameter. For each category, it was assumed that 10 wells were installed at each location and that all well screens were 5 feet [1.52m] in length. Other considerations included costs for materials, labor, waste generation, per diem, well development, reporting, and production rates (also a cost driver based on associated labor requirements). According to these conservative estimates, cost savings for DP well installations range from approximately 32 to 68 percent (Figure 5-1). Highest percentage installation savings can be derived when using smaller diameter wells at deeper total depths. Assuming that 500 wells per state would be installed per year, the total anticipated DoD savings per year due to DP well installations range from approximately $12M to close to $80M per year (Figure 5-2). Since the majority of DP wells are less than 2 inches [5.08cm] in diameter, the low end DoD cost savings estimate is approximately $20M per year. Using these conservative estimates, industry savings could exceed $200M dollars per year with as few as 1,300 DP wells per state per year. Life cycle cost savings associated with DP wells is significant, ranging from approximately 17 to 47 percent, and tends to be highest for smaller diameter wells installed to deeper depths (Table 5-5).

Users must consider that smaller diameter wells may not be appropriate for some applications (e.g., when a pump is to be used), that deeper wells can be more challenging for DP installation methods, and success will depend upon the soil lithology and resistance to hydraulic or hammer installation techniques. However, when DP well installations are appropriate, significant reduction of worker exposure to hazardous materials can be realized, and time requirements can be reduced relative to conventional drilled wells.

Furthermore, additional cost savings are anticipated when one implements the Kram and Farrar WDS method, when DP well installations are coupled with production efforts such as initial or supplemental site characterization, and when conducting hydraulic assessments using pneumatic slug tests.

6.0 IMPLEMENTATION ISSUES

6.1 Environmental Checklist

As with conventional drilled monitoring wells, permits may be required for well installation and waste generation and handling activities. Well installation regulations include state and federal regulations and often reference ASTM and EPA guidance documents. In California, a Department of Water Resources (1981) Well Bulletin exists that includes guidance for well installations. As with many states, the California Well Bulletin does not yet address DP well installation requirements. Whenever a monitoring well is installed into a beneficial use water-bearing zone, a well installation permit must be obtain by the lead regulatory authority, which is typically managed through county water resources, groundwater, or flood control entities. If a beneficial use water-bearing zone is not accessed, or if a confining zone exists between the well screen and beneficial use aquifer, a well permit exemption can be obtained. Most states do not yet have guidelines established for DP well installations. However, several counties have developed guidance for obtaining a regulatory variance (San Diego County, 2004). Documentation of the well abandonment and decommissioning efforts are also often required through a permit process once the site managers conclude that there is no longer a need for the well.

Solid and liquid wastes will be generated during well installation, development, and decommissioning and removal activities. Waste handling permits are typically managed through the county or state regulatory agency. In California, the Regional Water Quality Control Board oversees such activities, and must be contacted to obtain essential waste tracking guidance and essential forms. When on a U.S. military base, the base environmental coordinator typically maintains a base wide permit that can be amended to incorporate waste handling needs. In addition, the base often has a staging area for management and logistical support.

6.2 Other Regulatory Issues

Several actions were taken throughout the project to promote regulatory acceptance of the demonstration program and its eventual results, and to assure compliance with applicable regulations at all field sites. During development of the project workplan, the research team held conference calls with regulatory review bodies including the Groundwater Monitoring Forum and the Direct-Push Technology Forum. Both forums are composed of state and regional regulators. In addition, a Technical Advisory Committee comprised of leading industry and government experts in well applications was established for the Port Hueneme portion of the demonstration. These bodies reviewed the draft workplan, and their comments were addressed in revisions leading to the final workplan. Furthermore, the EPA Environmental Technology Verification (ETV) program actively participated in the development of the workplan and assisted with coordination of input from participating regulators.

The well comparison study was also presented to the Sampling, Site Characterization, and Monitoring 2002 Work Group of the Interstate Technology Regulatory Council (ITRC) program at their annual kickoff meeting in Baltimore, MD in February 2001. The work group received the project enthusiastically, and it was found to meet all the criteria for ITRC involvement. These criteria include:

- A regulatory barrier exists in most states;

- DOD and DOE are affected by the problem;
- The issue has broad national applicability;
- The effort builds on previous efforts;
- The product (e.g., findings) will set precedent;
- The outcome can be applied to other projects;
- Reciprocity among states can result from the project.

Funding for active involvement of the ITRC Sampling, Characterization, and Monitoring (SCM) Work Team was not available until 2002. Shortly after ESTCP project team members presented their most recent findings to the ITRC work group, it was decided that a Technical Regulatory guidance document would be pursued with the help of ESTCP project team members Bill Major, Louise Parker, and Dr. Mark Kram. This document was completed in March 2006. An on-line workshop aimed at DP wells and related DP technologies has been met with overwhelming support.

Dr. Kram and other members of this demonstration team were invited to meet with regulators from the State of Florida, State of Ohio, State of Indiana, State of California, and elsewhere to try to convince other state and federal partners to accept the use of DP wells for LTM applications. Furthermore, Dr. Kram and Bill Major gave several Port Hueneme demonstration site tours to local regulators, local environmental service providers, and graduate students (several who have recently become regulators) from UC Santa Barbara.

While technology transfer efforts to-date have been very successful, another powerful technology transfer vehicle includes the marketing and sales efforts of industry service providers and DP well supply vendors. Industry was involved extensively during the demonstration. Applied Research Associates, Inc. (ARA), a leading provider of CPT equipment and services including DP well installation participated directly on the project team and was responsible for executing many of design-related and analytical tasks within the project. Geoprobe Systems, Inc. (Geoprobe), the foremost manufacturer of percussion hammer DP platforms and related equipment, as well as a DP service provider, conducted well installations at two of the test sites. In addition, ARA, Geoprobe, and many other industry players both contributed material to and participated in review of the ASTM standards that were created, and have been kept abreast of the progress of the project throughout its duration. The ASTM task group generating direct-push technology standards and guidance documents includes representatives from DP user groups and equipment manufacturers. Jeff Farrar, the leader of the task group on DP standards generation, is the current Chairman of ASTM Subcommittee on Soil and Rock (D18.21).

This demonstration project has satisfied the major objectives set forth at the outset, many of which were designed to promote user acceptance of DP wells for LTM. Among the objectives that have been met are:

- Careful design of a technically rigorous research methodology for comparing the performance of DP wells to HSA wells;
- Generation of a consistent data set for conducting such a comparison, using regulatory accepted field and laboratory protocols;
- Performance of appropriate statistical tests for evaluating the performance of DP wells versus HSA wells using a broad suite of analytes and other water quality measurements;

- Performance of appropriate statistical tests for evaluating the hydraulic performance of DP wells versus HSA wells;
- Creation of a comprehensive project database to aid in management and analysis of the data set generated;
- Publication of articles, technical reports, and a student masters thesis;
- Promulgation of two ASTM standards pertaining to the use of DP well for groundwater monitoring;
- Development of an ITRC Technical Regulatory guidance document for the long-term use of DP wells;
- Development of a well design software package to overcome regulatory criticism and concerns;
- Presentation at key industry and government conferences;
- Field tours of the sites provided to regulators, UCSB graduate students (some of whom have become regulators), and key industry personnel; and
- Active participation with industry and environmental regulatory committees and cooperatives.

Future technology transfer vehicles include:
- Advertisement and presentation of ITRC workshop;
- Continued release and dissemination of ITRC Technical Regulatory guide;
- Utilization of DoD technology transfer vehicles such as conferences, RITS, NAVFAC ESC announcements, and final report dissemination; and
- Continued notification of DoD and industry users and DP service and materials providers.

6.3 End-User Issues

End-users would include responsible parties, DoD, and other government and private entities. Key end-user and industry stakeholder buy-in is predicated on the regulatory acceptance of DP wells for LTM applications. Early on, the team recognized that design of a comparison effort could benefit greatly from the knowledge and guidance of respected technical experts from private industry, government, and academia. In addition to the direct interactions with regulator-only organizations, a DoD Task Force on Direct-Push Groundwater Monitoring Wells was convened during one of the preliminary studies that led up to the current project. This task force also met during the planning and execution stages of this demonstration. In addition, a Technical Advisory Committee (TAC) comprised of leading industry and government experts in well applications was established for the Port Hueneme efforts preceding this demonstration. The TAC assisted with initial project planning, experimental design, and review of Dr. Kram's original work plan for the Port Hueneme test cells. This team was reconvened for a workshop in December of 2001 to assist with Phase I review (for all demonstration sites) and to help plan for Phase II design alterations. Expert technical oversight weighed heavily on the ultimate success of this demonstration, as regulatory buy-in was facilitated through credibility of the experimental design, execution, and data assessment activities supported through consensus.

In addition to design and execution of this well comparison demonstration, another critical project accomplishment included assistance with the development of two ASTM standards. These standards, entitled "Standard Guide for Installation of Direct-Push Groundwater

Monitoring Wells" (D6724) and “Standard Practice for Direct-push Installation of Pre-packed Screen Monitoring Wells in Unconsolidated Aquifers” (D6725) were co-authored and edited by members of the project team. In addition to providing industry practitioners with guidance on the use and design of DP wells, these documents provide regulators with publications they can refer to as benchmarks for quality control. Furthermore, these standards can be used as procurement specifications, to develop standard operating procedures, and for training purposes.

Building upon the success of the ASTM standards and initial well comparison technical report (Kram *et al.*, 2001), pursuit of an ITRC Technical Regulatory guidance document through collaboration between project team members and regulators was initiated. Case studies, statistical comparisons, and background information derived from this demonstration effort were included in the guide. This key regulatory document was released in March 2006 (ITRC, 2006), and an on-line ITRC DP well workshop has convened four times as of this writing. Of all the written products, this single document represents perhaps the most significant removal of technical and regulatory concerns and barriers, as it represents an implied regulatory support of properly designed and installed DP wells for LTM.

During the course of this demonstration, several technical barriers were directly addressed to build support for regulatory approval. For instance, when the demonstration was initiated, regulators were concerned about DP wells that do not have filter packs. For wells that do have filter packs, until recently, DP filter pack and screen designs did not conform to ASTM D5092. As a result, Kram and Farrar developed a software package to enable users to design wells in accordance with ASTM using soil classifications derived from penetrometer probe data (U.S. Patent 6,317,694). Since penetrometers can also be used to install DP wells, this allows for unprecedented customization of DP well designs with significant cost savings (e.g., versus conventional soil sampling and grain size distribution assessment). While this software and concept is protected under a DoD patent, licensing to private industry partners is currently underway.

When the project was initially funded, pre-pack filters did not yet exist, or were not commonly used by industry. This was a concern on the part of regulators, as tremmie application of filter packs in small diameter well annular spacing posed significant logistical challenges, which is one of the main reasons regulators did not initially accept DP wells. Due at least in part to this demonstration effort, and to the close communication project members have maintained with industry suppliers, users now have several pre-pack options that are commercially available. Some, but not all of the ASTM recommended filter pack and screen combinations are commercially available. Team members are encouraging industry representatives to conform to the ASTM recommended designs and make these available to the DP well user community.

Hydraulic performance of DP wells was also a key source of regulatory concern. Regulators and industry users were not sure if hydraulic conductivity (K) measurements in DP wells matched similar measurements in conventional drilled wells. The hydraulic tests partially supported by this project illustrate that K values collected from highly permeable soils using slightly modified commercially available slug test equipment can be determined using DP wells. This component of the demonstration is significant for several reasons. It demonstrates to regulators that DP wells can be used for hydraulic measurements, and that very short duration (e.g., less than 5

second) slug tests yield reproducible and comparable results to those measured in nearby drilled wells. Values were verified by triplicate runs, performing slug-in and slug-out tests, and by conducting conventional pumping aquifer tests for comparison.

Future technology transfer plans include:

- Advertisement and presentation of ITRC workshop;
- Continued release and dissemination of ITRC Technical Regulatory guide;
- Utilization of DoD technology transfer vehicles such as conferences, RITS, NAVFAC ESC announcements, and final report dissemination;
- Licensing of the Kram and Farrar well design software package; and
- Continued notification of DoD and industry users and DP service and materials providers.

7.0 REFERENCES

ASTM D 4044, Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers.

ASTM D 1498, Standard Practice for Oxidation-Reduction Potential of Water.

ASTM D 6724, Standard Guide for Installation of Direct-push Ground Water Monitoring Wells.

ASTM D 6725, Standard Practice for Direct-push Installation of Pre-packed Screen Monitoring Wells in Unconsolidated Aquifers.

Bartlett, S.A., Robbins, G.A., Mandrick, J.D., Barcelona, M.J., McCall, W., and Kram, M.L., 2004, Comparison of Hydraulic Conductivity Determinations in Direct-push and Conventional Wells, Naval Facilities Engineering Service Center Technical Report, TR-2252-ENV, October, 2004, 88pp.

Bianchi, J.C., and Farrington, S.P., 2000. *Direct-push Monitoring Point Assessment Hanscom Air Force Base*, Applied Research Associates, Inc.

Bower, H., and Rice, R. C., 1976. *A Slug test for Determining Hydraulic Conductivity of Unconfined Aquifers with Completely or Partially Penetrating Wells*, Water Resources Research, Vol. 12, No. 3, 1976, pp. 423-423.

British Petroleum and USEPA, 2002. Monitoring Well Comparison Study: An Evaluation of Direct-push versus Conventional Monitoring Wells, 80pp.

Butler, J.J., Jr., Healey, J.M., McCall, G.W., Garnett, E.J., and S.P. Loheide II, 2002. *Hydraulic Tests with Direct-Push Equipment*, Ground Water Journal, Association of Ground Water Scientists & Engineers, Volume 40, Number 1, January-February, pp. 25-36.

Conover, W.J., 1980. Practical Nonparametric Statistics, John Wiley & Sons, NY.

Crumbling, D., 2000. Innovations in Site Characterization Case Study: Direct-push Comparison For Hanscom Air Force Base, US EPA Technology Innovation Office, March, 2000.

Driscoll, F.G., 1986. Groundwater and Wells. Johnson Filtration Systems, Inc., St. Paul, MN, 5512.

Farrington, S.P., and W.L. Bratton, 1997. Measuring Fuel Contamination Using Cone Penetration Testing and High Speed Gas Chromatography, Final Report to U.S. Department of Energy, Morgantown Technology Center, Morgantown, WV, February 1997.

Feller, W., 1968. An Introduction to Probability Theory and Its Applications, Volume I, John Wiley & Sons, NY.

Gildea, M.L., W.L. Bratton, J.D. Shinn, *Demonstration and Evaluation of the Air Force Site Characterization and Analysis Penetrometer System in Support of Natural Attenuation Initiatives*, Under Contract F0863 5-93 -C-0020, SETA Subtask 8.01.1, Report to Air Force Armstrong Laboratory, Tyndall AFB, FL, February 1995.

Grant, C. L., T. F. Jenkins, A. R. Mudambi, 1996. Comparison Criteria for Environmental Chemical Analyses of Split Samples Sent to Different Laboratories, Special Report 96-9, CRREL, May, 1996.

Hald, A., 1952. Statistical Theory with Engineering Applications, John Wiley & Sons, NY.

Hvorslev, M. J., 1951. Time Lag and Soil Permeability in Ground-Water Observations, Waterways Experiment Station, Corps of Engineers, U.S. Army, Bulletin No. 36, 1951, p.50.

Iman, R.L., 1974. *Use of a t-statistic as an Approximation to the Exact Distribution of the Wilcoxon Signed Ranks Test Statistic*, Communications in Statistics, v.3.

ITRC, 2006. The Use of Direct-push Well Technology for Long-term Environmental Monitoring in Groundwater Investigations, Technical Regulatory Guidance, March, 2006, 71pp.

Kram, Mark L., 1998, *Use of SCAPS Petroleum Hydrocarbon Sensor Technology for Real-Time Indirect DNAPL Detection*, Journal of Soil Contamination, Vol. 17, No. 1, 1998, p.73-86.

Kram, Mark, D. Lorenzana, J. Michaelsen, E. Lory, 2001. Performance Comparison: Direct-Push Wells Versus Drilled Wells, Naval Facilities Engineering Service Center Technical Report, TR-2120-ENV, January 2001, 55pp.

Kram, Mark, D. Lorenzana, J. Michaelsen, W. Major, L. Parker, C. Antworth, and T. McHale, 2003. Direct-Push Wells Prove Effective for Long-Term Ground Water Monitoring, Waterwell Journal, v. 57, no. 4, April 2003, p. 16-18.

Kram, Mark L., Arturo A. Keller, Steve M. Massick, and Leroy E. Laverman, 2004. *Complex NAPL Site Characterization Using Fluorescence, Part 1: Selection of Excitation Wavelength Based on NAPL Composition*, Soil and Sediment Contamination: an International Journal, March/April, v.13, no.2, pp.103-118.

Kram, Mark L., Gary Robbins, Renduo Zhang, Lanbo Liu, Norm Jones, 2006a. *Detailed Hydraulic Assessment Using a High-Resolution Piezocone Coupled to the GeoVIS*, in Proceedings of the North American Environmental Field Conference, Tampa, FL.

Kram, Mark L., 2006. *DNAPL Characterization Methods and Approaches: Performance and Cost Comparisons*, in The Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring, D. M. Nielsen, Editor, CRC Press/Taylor & Francis Publishers, Boca Raton, FL, p.473-516.

Lieberman, S.H., G.A. Theriault, S.S. Cooper, P.G. Malone, R.S. Olsen, and P.W. Lurk, 1991, *Rapid Subsurface In Situ Field Screening of Petroleum Hydrocarbon Contamination Using Laser Induced Fluorescence Over Optical Fibers*, Proceedings of the Symposium on Field Screening Methods for Hazardous Wastes and Toxic Chemicals, U.S. EPA, Washington, CD, 1991, pp. 57-63.

Lieberman, S.H., D.S. Knowles, J. Kertesz, P.M. Stang, and D. Mendez, 1997, *Cone Penetrometer Deployed In Situ Video Microscope for Characterizing Subsurface Soil Properties*, Proceedings of the Symposium on Field Screening Methods for Hazardous Wastes and Toxic Chemicals, Air and Waste Management Association, Pittsburgh, PA, 1997, pp. 579-587.

Lieberman, S.H., G.W. Anderson, V. Games, J. Costanza, and A. Taer, 1998, *Use of a Cone Penetrometer Deployed Video-Imaging System for In Situ detection of NAPLs in Subsurface Soil Environments*, Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water, National Ground Water Association, Westerville, OH, 1998, pp. 384-389.

McCall, W., Stover, S., Enos, C., and Fuhrmann, G., 1997, *Field Comparison of Direct-push Pre-packed Screen Monitoring Wells to Paired HSA 2" PVC Wells*. In Superfund XVIII Conference Proceedings, Volume 2. p. 647 – 655, E.J. Krause and Assoc., Washington, D.C.

McCall, W., 1999, *Field Comparison of Paired direct-push and HSA Monitoring wells,* in Natural Attenuation of Chlorinated Solvents, Petroleum Hydrocarbons, and Other Organic Compounds, April 19-22, 1999, Alleman and Leeson, eds.

McCall, W., D.M. Nielsen, S.P. Farrington, and T.M. Christy, 2006, *Use of Direct-Push Technologies in Environmental Site Characterization and Ground-Water Monitoring*, in Practical Handbook of Environmental Site Characterization and Ground-Water Monitoring, Second Edition, 2006, pp. 345-471, D.M. Nielsen ed.

Royston, J.P., 1982. *An Extension of Shapiro and Wilk's W Test for Normality to Large Samples*, Applied Statistics, v. 31.

San Diego County, 2004. SAM Manual, Appendix B, Monitoring Well/Boring Permit and Standards, Section D: Small Diameter Well Variance Guideline, San Diego, CA, p. B-20 to B-36.

SAS Institute Inc., 1990. SAS Procedures Guide, Version 6, 3rd Ed., Cary NC 1990.

Shapiro, S.S. and M.B. Wilk, 1965. *An Analysis of Variance Test for Normality (complete samples)*, Biometrika, v.52, no.3 and 4, p.591-611.

State of California, 1981. California Department of Water Resources Bulletin 74-81: Water Well Standards: State of California, December 1981, 92 p.

Steel. R.G.D., and J.H. Torrie, 1990. Principles and Procedures of Statistics, McGraw-Hill, NY.

Walpole, R., and R. Myers, 1978. Probability and Statistics for Engineers and Scientists, Macmillan, NY.

US Department of Defense, 1995. Defense Environmental Restoration Program, Annual Report to Congress for Fiscal Year 1995.

US Environmental Protection Agency, 2004. Cleaning Up the Nation's Waste Sites: Markets and Technology Trends, 2004 Edition; http://www.epa.gov/superfund/news/30years.htm.

US Environmental Protection Agency, 2000. Superfund: 20 Years of Protecting Human Health and the Environment, U.S. EPA Publication EPA 540-R-00-007.

US Environmental Protection Agency, 1996. Drinking Water Regulations and Health Advisories, Office of Water, Washington, DC, February 1996.

US Environmental Protection Agency, 1989. Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities, Office of Solid Waste Management Division, Washington, DC, February.

US Environmental Protection Agency, 1988a. Guidance for Conducting Remedial Investigations/Feasibility Studies Under CERCLA.

US Environmental Protection Agency, 1988b. Laboratory Data Validation Functional Guidelines for Evaluating Organic Analyses, Hazardous Waste Site Evaluation Division, Washington, DC.

US Environmental Protection Agency, 1986. Test Methods for Evaluating Solid Waste, Physical/Chemical Methods, SW-846, 3rd Edition.

US Patent 6,317,694, November 13, 2001, Method and Apparatus for Selecting a Sand Pack Mesh for a Filter Pack and Well Casing Slot Size for a Well, Kram, Mark L., and Farrar, Jeffrey A.

8.0 POINTS OF CONTACT

Project Team Contacts	Site Contacts
Principal Investigator William Major Naval Facilities Engineering Service Center NAVFAC ESC EV411 1100 23rd Ave. Port Hueneme, CA 93043-4370 Phone: 805-982-1808 Fax: 805-982-4304 ***William.major@navy.mil*** Project Management, Tech Reg Preparation, Technical and Strategic Management, Presentations to Regulators	William Major Naval Facilities Engineering Service Center NAVFAC ESC EV411 1100 23rd Ave. Port Hueneme, CA 93043-4370 Phone: 805-982-1808 Fax: 805-982-4304 William.major@navy.mil
Louise Parker CRREL 72 Lyme Rd. Hanover NH, 03755-1290 Phone: 603-646-4393 Fax: 603-646-4640 lparker@crrel.usace.army.mil CRREL Management, Statistical Analyses, Report Preparation, Tech Reg Preparation, Presentation to Regulators	Louise Parker CRREL 72 Lyme Rd. Hanover NH, 03755-1290 Phone: 603-646-4393 Fax: 603-646-4640 lparker@crrel.usace.army.mil
Tim McHale Test Location Manager Dover National Test Site Building 909 Arnold Drive Extended Dover AFB, DE 19902 Phone: 302-67-4102 Fax: 302-677-4080 tim.mchale@dover.af.mil Dover and Tyndall Management	Tim McHale Test Location Manager Dover National Test Site Building 909 Arnold Drive Extended Dover AFB, DE 19902 Phone: 302-67-4102 Fax: 302-677-4080 tim.mchale@dover.af.mil

Mark Kram, Ph.D. Naval Facilities Engineering Service Center NAVFAC ESC Code 413 1100 23rd Ave. Port Hueneme, CA 93043-4370 Phone: 805-982-2669; Fax: 805-982-4304 mark.kram@navy.mil Project Co-Management, Tech Reg Preparation, Standard Preparation, Technical and Strategic Management, Hydraulic Assessments, Report Preparation, Experimental Design, Well Design, Presentations to Regulators	
Joel Michelsen, Ph.D. Geography Department University of California Santa Barbara, CA 93106 (805) 893-3146 joel@geog.ucsb.edu Statistical Analyses, Report Preparation	

Dated Signature of Project Lead:

William Major, Project Lead

Date

APPENDICIES

Appendix A: Quality Assurance Project Plan (QAPP)
Appendix B: Hydraulic Conductivity Comparison
Appendix C: Phase II Work Plan

APPENDIX A

QUALITY ASSURANCE PROJECT PLAN

DEMONSTRATION/VALIDATION OF

LONG-TERM MONITORING USING WELLS INSTALLED BY DIRECT PUSH TECHNOLOGIES

Quality Assurance Project Plan

1.1 Purpose and Scope of the Plan

This Quality Assurance Project Plan (QAPP) has been prepared to document the quality assurance protocols for execution of the study. The purpose of this QAPP is to define the field and laboratory data requirements for the experiment and to ensure that the data are of sufficient quality to support the end use of the data. The QAPP defines the policy, organization, functional activities, and quality assurance (QA) and quality control (QC) protocols that will be used to meet the objectives of this investigation. Descriptions of the procedures associated with the field programs, including sample collection, sample custody, laboratory analysis, and QA/QC for this project are described in this document. Adherence to the procedures described in this QAPP should generate data that are scientifically sound, valid, defensible, and of known, acceptable, and documented quality.

1.2 Quality Assurance Responsibilities

All project personnel have a responsibility for maintaining and documenting compliance with the quality procedures prescribed in this document. The AFRL Principal Investigator has ultimate responsibility for the quality of the demonstration. The field staff are responsible for documenting and reporting any suspected technical and QA non-conformances, and suspected deficiencies during any field activity. The AFRL Principal Investigator, in conjunction with the QC Coordinator, will be responsible for initiating corrective actions in field activity. Analytical data quality issues are primarily handled at the bench level by the analyst who reviews the sample preparation or extraction procedures, and performs the instrument calibration and analysis. The analyst is responsible for corrective action at this level. If a problem with analytical quality persists or its cause cannot be identified, the matter should be referred to the Laboratory Manager or QC Coordinator for further investigation.

1.3 Data Quality Parameters

The quality of the field and analytical data will be evaluated using precision, accuracy, representativeness, completeness, and comparability (PARCC) parameters, which are quantitative and qualitative statements that describe data quality. The PARCC parameters will be used to determine whether the data quality objectives of this investigation have been met by comparing QC sample results and standard procedures with acceptance criteria established for this project. Each of the PARCC parameters that will be used for data evaluation are defined and discussed in relation to specific project activities below.

1.3.1. Accuracy

Accuracy is the degree of agreement of a measurement or an average of measurements with an accepted reference or “true” value, and is a measure of bias in the system. The accuracy of a measurement system is impacted by errors introduced through the sampling process, field contamination, preservation, handling, sample matrix, sample preparation, and analytical techniques.

Accuracy is evaluated by the following equation:

$$\text{Percent Recovery} = \frac{\text{A - B}}{\text{C}} \times 100 \tag{7}$$

where:

A = concentration of analyte in a spiked sample
B = concentration of analyte in an unspiked sample
C = concentration of spike added.

For this project, accuracy will be assessed and controlled by the results of the following QC samples, which contain known concentrations of specific analytes (spiked):

- Matrix spike (MS) and matrix spike duplicates (MSD)
- Laboratory control samples (LCS) and LCS duplicates (LCSD)

As these samples are analyzed, spike recoveries will be calculated and compared to pre-established acceptance limits. Acceptance limits are based on previously established laboratory performance or specified by the analytical methods. The control limits reflect the minimum and maximum recoveries expected for individual measurements for an in-control system. Recoveries outside the established limits indicate error in addition to normal measurement error, and the possible need for corrective action. Corrective action may include re-calibrating the instrument, reanalyzing the QC samples, re-analyzing the sample batch, re-preparation of the sample batch, or flagging the data (if problems can not be resolved). For contaminated samples, matrix spike recoveries may be dependent upon sample homogeneity, matrix interference, and dilution requirements.

Laboratory accuracy will be evaluated using the results for MS/MSD, and LCS/LCSD sample analyses. As with precision, the accuracy objectives for the data are based on laboratory established limits, and vary with the specific analyte.

Although there is no way to quantitatively measure the accuracy of the field program using percent recovery, some aspects of accuracy can be assessed, such as comparing the length of the water-level probe to another measuring tape of known length and proper calibration of the field instruments.

1.3.2. Precision

Precision is the reproducibility of measurements under a given set of conditions. For large data sets, precision is expressed as the variability of a group of measurements compared to their average value (i.e., standard deviation). For duplicate measurements, precision is expressed as the relative percent difference (RPD) of a data pair and is calculated using the following equation:

$$\text{RPD} = \frac{[\text{A - B}]}{([\text{A} + \text{B}]/2)} \times 100 \tag{8}$$

where: A and B are the reported concentrations for sample duplicate analyses.

For this project, precision will be assessed by calculating the RPD of the MS/MSD sample pairs and the duplicate and replicate sample pairs and comparing the results to

laboratory-established RPD control limits. Precision of duplicate samples is dependent upon sample homogeneity. The data quality objectives for precision during this program are based on laboratory established control limits, which are specific to each analyte.

The analyst, group leader, or technical advisor is responsible for investigating data outside the QC limits. Corrective action may include re-calibrating the instrument, re-analyzing QC samples, re-analyzing samples, or flagging the data.

Sampling precision in the field program is affected by the procedures used for sample collection, handling, and transportation. To reduce the variability that may be introduced during sampling, the Work Plan outlines the standard sampling, handling, and shipping procedures that will be used for each sampling program. The use of these procedures should minimize variability in the sampling process.

1.3.3. Representativeness

Representativeness is a qualitative expression of the degree to which sample data accurately and precisely represents a characteristic of a population, a sampling point, or an environmental condition. Representativeness is maximized by ensuring that, for a given project, the number and location of sampling points and sample collection and analysis techniques are appropriate for the specific investigation, and that the sampling and analysis program will provide information that reflects “true” site conditions. Representativeness will be evaluated by analysis of laboratory method and equipment blanks, and duplicate or replicate samples. Laboratory method and equipment blanks will be used with duplicates or replicates to evaluate laboratory performance.

Representativeness is also evaluated using holding-time criteria, which reflect the length of time that a sample or extract remains representative of the environmental conditions after sample collection. Holding time are compared to standard method-specific holding times accepted by the EPA. All holding times within the acceptance criteria are considered representative. Those holding times outside of EPA acceptance criteria are qualitatively evaluated to determine the effect on sample representativeness.

The representativeness of the field data is determined by the design of the data collection procedures. The sampling and field measurement procedures to be used are based on the needs of the study, the existing analytical data, hydrogeology, the physical setting of the field sites, and the past land use history. Representativeness of the field sampling procedures and the field measurements will be evaluated by comparing the sampling and measurement procedures used in the field to the procedures outlined in this Work Plan. In addition, the results of equipment blank samples will be used to evaluate the representativeness of field sampling procedures. Contaminants detected in equipment blanks are indications that the decontamination procedures are not completely effective, and that contaminants detected at specific sites may be attributable to cross-contamination rather than the environment.

1.3.4. Comparability

Comparability is a qualitative parameter that expresses the confidence that one data set may be compared to another. Comparability of data is achieved through the use of standardized methods for sample collection and analysis, and the use of standardized

units of measure. The comparability of the field sampling procedures and field measurement data will be evaluated by comparing them to previous sampling rounds.

1.3.5. Completeness

Completeness is defined as the percentage of valid data relative to the total number of analytes and is evaluated using precision, accuracy, and holding time criteria. Completeness will be calculated using the following equation:

$$\text{Completeness} = \frac{\text{Valid Data}}{\text{TotalData}} \times 100 \tag{9}$$

Project completeness is determined at the conclusion of the data validation and is calculated by dividing the number of valid sample results by the total number of samples analyzed. The completeness objective for this project is 90 percent for all data and is based on USEPA guidelines (USEPA, 1988a).

Completeness of the field program will be evaluated to ensure that the appropriate number of samples were collected for analysis, and that field data of the type and quantity outlined in the Work Plan were collected. Completeness of the field investigations will be evaluated by comparing the actual number of samples and the actual quantity of data that were collected to the requirements outlined in the Work Plan.

1.3.6. Method Detection Limit (MDL)

Method detection limits will be determined in accordance with the procedures in SW-846 and Appendix B of 40 CFR Part 136. This procedure includes analyzing seven or more prepared spikes or standards in reagent water at levels 3-5 times the estimated detection limit. The standard deviation of the replicate measurements is calculated, and the MDL is computed as shown below in Equation (13). The MDL calculated by the procedure described above is defined as "The minimum concentration of a substance that can be measured in reagent water and reported with a 99% confidence that the analyte concentration is greater than zero."

$$\text{MDL} = t_{(n-1,\ 0.99)}s \tag{10}$$

where: $t_{(n-1,\ 0.99)}$ = Students' t value for a one-sided, 99% confidence level and a standard deviation estimate with n-1 degrees of freedom; s = standard deviation of replicate analyses of matrix spikes (reagent water).

1.4 Calibration Procedures, Quality Control Checks, and Corrective Action

The study has field and laboratory components, each with it's own calibration procedures, quality control checks, and corrective actions. The sections below discuss these plan elements with regard to each study component.

1.4.1. Field Equipment Calibration

The field equipment to be used during the groundwater sampling program includes a water-level sounder, a pH, specific conductance, dissolved oxygen, temperature, and turbidity meter, and an organic vapor meter. Electric water-level sounders will be checked before the beginning of the field activities by comparing the scale on the water-level tape against an engineering measurement tape. The multi-probe field instrument

selected to measure pH, Turbidity, Dissolved Oxygen, Temperature, and Specific Conductivity will be calibrated daily prior to use according to the manufacturer's instructions. A calibration log will be kept for each instrument, in which will be recorded measurements demonstrating successful completion of the required calibration and the expiration dates of any reference solutions used. Any organic vapor detectors including flame ionization detectors (FIDs) and photoionization detectors (PIDs) will be calibrated daily prior to use and any time that instrument drift is suspected. In addition, calibration will be checked at the conclusion of each day of use in order to evaluate instrument performance. Instruments will not be adjusted before the final calibration check has been performed and recorded. Calibration procedures will be documented in the log book or on the appropriate field form. Calibration gases that have a shelf life will not be used past the expiration date.

1.4.2. Analytical Instrument Calibration

Calibration of instrumentation is required to ensure that the analytical system is operating correctly and functioning at the sensitivity necessary to meet established reporting limits (i.e., PQLs). Each instrument will be calibrated with standard solutions appropriate to the type of instrument and the linear range established for the analytical method.

Analytical instruments will be calibrated using standards in accordance with the specified analytical methods and manufacturer's procedures. At a minimum, written calibration procedures include the equipment to be calibrated, the reference standards used for calibration, the calibration techniques, actions, acceptable performance tolerances, frequency of calibration, and calibration documentation format. Records of standard preparation and instrument calibration will be maintained. Instrument calibration will include daily checks using standards prepared independently of the calibration standards and instrument response will be evaluated against established criteria. The analysis log book, maintained for each analytical instrument, will include at a minimum: the date and time of calibration, the initials of the person performing the calibration, the calibrator reference number and concentration. Instrument calibration procedures for specific instruments used for organic analyses are discussed in the following paragraphs.

1.4.2.1.Gas Chromatography

For Gas Chromatography, initial calibration consists of determining the linear range, establishing detection limits, and establishing retention time windows. The calibration will then be checked daily to ensure that the system calibration remains within specifications. If the daily calibration check does not meet established criteria, the system will be recalibrated.

Calibration standards will be prepared according to the standard operating procedure for the method. For the SW-846 8000 series methods, a calibration standard will be prepared for each analyte of interest at five concentration levels. One of these standards will be slightly above the method detection limit. The other standards will bracket the concentration range expected in the environmental samples, but not exceed the working range of the detector.

A reagent water blank will be run prior to calibration to show the absence of interferences. The calibration standards then will be introduced into the system and a

calibration curve will be generated for each analyte. The response factor for each analyte at each concentration will be calculated as follows:

$$\text{Response Factor (RF)} = \frac{\text{Total Area of Peak}^{(a)}}{\text{Mass Injected (in nanograms)}} \tag{11}$$

(a) For multiresponse analytes, the area from at least five major peaks shall be used for quantitation.

Acceptance criteria for instrument response linearity checks are based upon the correlation coefficient (r) of the best fit line for the calibration data points, or on the percent relative standard deviation (% RSD) for response factors calculated for each analyte at each level over the working range. The correlation coefficient is calculated as:

$$r = \frac{n\sum(xy) - \left(\sum x\right)\left(\sum y\right)}{\sqrt{\left[n\left(\sum x^2\right) - \left(\sum x^2\right)\right]\left[n\left(\sum y^2\right) - \left(\sum y^2\right)\right]}} \tag{12}$$

where: x = calibration concentrations
y = instrument response (peak area)
n = number of calibration points (x,y data pairs).

The percent RSD is calculated as:

$$\%RSD = \frac{SD}{\bar{c}} \times 100 \tag{13}$$

where:	%RSD	=	relative standard deviation
	$\bar{c}$	=	means of 5 initial RFs for a compound
	SD	=	standard deviation of the RFs for a compound

$$SD = s\sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left[\sum_{i=1}^{n} x_i\right]^2 / n}{n-1}} \tag{14}$$

If the coefficient of correlation, r, is greater than or equal to 0.995, or the %RSD is less than or equal to 20 percent, the calibration is considered valid. The use of r or %RSD is instrument specific, and only one of these criteria will be used on each instrument.

The calibration curve and response factors will be checked daily by injecting at least one calibration standard, usually the mid-range standard. The percent difference between initial and continuing response factors will be calculated using the following equation:

$$\%\ \text{Difference} = \frac{\left(RF_1 - RF_c\right)}{RF_1} \times 100 \tag{15}$$

where: RF_1 = average relative response factor from initial calibration
RF_2 = response factor from continuing calibration

An acceptable percent difference will be within plus or minus 15 percent.

Retention time windows must be established for each analyte during initial calibration per SW 846, Method 8000. The retention time window must be checked prior to sample analysis using the calibration check standard. A warning limit specific to the method will be used. If the standard fails to meet the retention time window, the instrument will be recalibrated.

1.4.2.2.Gas Chromatography/Mass Spectroscopy

For Gas Chromatography/Mass Spectrometry (GC/MS), each day prior to analysis of samples for VOCs, the instrument will be tuned with bromofluorobenzene (BFB) (according to the tuning criteria specified in the USEPA Contract Laboratory Program [CLP]). No samples will be analyzed until the instrument has met tuning criteria.

After the instrument has met tuning criteria, it will then be calibrated for all target compounds. An initial calibration curve will be produced, and certain compounds referred to as System Performance Calibration Compounds (SPCC) and Continuing Calibration Compounds (CCC) will be evaluated to ensure that the system is within calibration. If the daily SPCCs and CCCs do not meet the established criteria, the system will be recalibrated.

Calibration standards at a minimum of five concentrations will be prepared by secondary dilution of stock standards. All or a subset of the compounds listed in EPA Methods 8260 can be used as calibration standards.

Each calibration solution including internal standards and surrogates will be introduced according to EPA Method 5030 for volatile compounds. A relative response factor (RF) will be calculated for each compound relative to the internal standard whose retention time is closest to the compound being measured. The RF is calculated as follows:

$$RF = \frac{(A_x C_{is})}{(A_{is} C_x)} \qquad (16)$$

where: A_x = Area of characteristic ion for the compound being measured
A_{is} = Area of characteristic ion for the specific internal standard
C_{is} = Concentration of the specific internal standard
C_x = Concentration of the compound being measured.

The average relative response factor (RF1) will be calculated for each compound using the values from the five-point calibration. A system performance check must be made before the calibration is accepted as valid. The SPCCs are checked for a minimum average relative response factor. The five volatile SPCCs are chloromethane, 1,1-dichloroethane, bromoform, 1,1,2,2-tetrachloroethane, and chlorobenzene. The minimum acceptable average relative response factor for volatile compounds is 0.300 (0.250 for bromoform).

The percent relative standard deviation (% RSD) for the CCCs will be calculated from the RFs in the initial calibration and must meet specified criteria. The volatile CCCs are

1,1-dichloroethane, 1,2-dichloropropane, toluene, ethylbenzene, and vinyl chloride. The formula used to calculate % RSD is:

$$\% \, RSD = \frac{SD}{\bar{c}} \times 100 \; \% \, RSD = D \times 100 \tag{17}$$

where:
- RSD = Relative Standard Deviation
- $\bar{c}$ = Mean of 5 initial RFs for a compound
- SD = Standard deviation of the RFs for a compound

$$SD = s\sqrt{\frac{\sum_{i=1}^{n} x_i^2 - \left[\sum_{i=1}^{n} x_i\right]^2 / n}{n-1}} \tag{18}$$

Every 12-hour shift, each GC/MS must be tuned by purging or injecting 4-bromofluorobenzene (BFB) for volatile compounds. Also, initial calibration of the GC/MS will be checked by analyzing a calibration standard (usually the mid level standard) and checking the SPCC and CCC performance. If the minimum relative response factors for SPCCs are not met, corrective action must be taken before samples are analyzed. The percent difference of relative response factor compared to the average relative response factor from the initial calibration is calculated as follows:

$$\% \, \mathrm{Difference} = \frac{(\mathrm{RF}_1 - \mathrm{RF}_c)}{\mathrm{RF}_1} \times 100 \tag{19}$$

where:
- RF_1 = Average relative response factor from initial calibration
- RF_c = Relative response factor from current calibration check standard.

If the percent difference criterion for each CCC compound is met, the initial calibration is assumed to be valid. If the criterion is not met for any CCC, corrective action must be taken. A new five-point calibration must be generated if the source of the problem cannot be found and corrected.

The internal standard responses and retention times in the CCC must be evaluated. If any internal standard retention time changes by more than 30 seconds from the last calibration check (12 hours), the system must be checked for malfunctions and corrected as necessary. If the extracted ion current profile (EICP) area for any of the internal standards changes by a factor of two from the last daily calibration standard check, the system must be checked for malfunctions and corrections made as necessary. All samples analyzed during the time the system was malfunctioning must be re-analyzed.

1.4.3. Standard/Reagent Preparation

Data accuracy is dependent upon the accuracy of the standards used for instrument calibration. To ensure the highest quality standard, primary reference standards used by AFRL and STL will be obtained from the National Institute of Standards Technology (NIST), EPA CRADA vendors, or other reliable commercial sources. When standards are received at the laboratory, the date received, supplier, lot number, purity,

concentration, and expiration date are recorded in a standards log book. Vendor certification for the standards are retained in the files.

Standards are obtained either in their pure form, or in stock or working standard solutions. Dilutions are made from vendor standards. All standards are given a standard identification number and the following information is recorded in the standards log book: 1) source of the standard, 2) the initial concentration of the standard, 3) the final concentration of the standard, 4) the volume of the standard that was diluted, the volume of the final solution, 5) the solvent and the source and lot number of the solvent used for standard preparation, and 6) the preparer's initials. All standards are validated prior to use.

Validation procedures for standards include a check for chromatographic purity and verification of the standard's concentration by comparing its response to a standard of the same analyte prepared at a different time or obtained from a different source. Reagents also are analyzed for purity; for example, every lot of dichloromethane (used for organic extraction) is analyzed for contaminants prior to use in the laboratory. Standards are checked routinely for signs of deterioration (e.g., discoloration, formation of precipitates, and changes in concentration) and are discarded if deterioration is suspected or the expiration date has passed. Expiration dates are based on vendor recommendation, the analytical method, or internal research. Stock solutions for VOCs are not to be held for more than 30 days. Fresh working calibration standards shall be prepared every week. Stock solutions for semi-volatile organic compounds shall not be held for more than 90 days. Dilutions below 1 ppm shall not be held more than 30 days.

1.4.4. Field Quality Control Checks

Internal quality control evaluates whether a method is performing within acceptable limits of precision and accuracy. On the sampling level, quality control samples used to assess field sampling techniques and environmental conditions during sample collection and transportation include duplicates, trip blanks, and equipment blanks.

1.4.4.1. Duplicates

Duplicate or replicate samples will be used to assess variability in the sample matrix and to assess sampling precision. The sampling procedures will be evaluated by comparing the analytical results of duplicate or replicate sample pairs. If the reported values for the sample pair are similar, the samples are considered to be representative of the environment. A large difference (greater than 40 percent) between the reported values for the sample pair indicates that there may have been a problem during sampling or analysis. Duplicate analyses will be used to evaluate precision by calculating the RPD between a duplicate sample and its associated environmental sample. The RPD will be compared to the MS/MSD QC limits for precision. Relative percent difference values within the QC guidelines indicate that good sampling and analytical procedures were followed. Relative percent difference values outside the QC limits indicate that sample may be heterogeneous, or that there may have been a problem during sampling and/or analysis.

1.4.4.2. Trip Blanks

Trip blanks will be used to evaluate representativeness by assessing whether VOCs were introduced into samples during handling, shipping, or storage at the laboratory. Trip blanks prepared by the laboratory will be included with each sample shipment that contains groundwater samples for VOC analysis.

1.4.4.3. Equipment Blanks

Equipment blanks will be used to assess the equipment decontamination procedures and evaluate whether the samples are representative of the environment. The results of each equipment blank analysis will be reviewed for the presence of target analytes. If target analytes are found, the data from the associated environmental samples will be evaluated to determine if they are representative of environmental conditions or the result of incomplete equipment decontamination.

1.4.5. Analytical Quality Control Checks

The general objectives of a laboratory QC program are to:

- Ensure that all procedures are documented, including any changes in administrative and/or technical procedures.
- Ensure that all analytical procedures are validated and conducted according to method guidelines.
- Monitor the performance of the laboratory using a systematic inspection program.
- Ensure that all data are properly archived.

Internal quality control for analytical services will be conducted by the laboratory in accordance to their standard operating procedures, the individual method requirements, and this QAPP. Before making significant changes to the QAPP or analytical methodology, the laboratory will notify AL/EQA in writing.

Laboratory quality control consists of two distinct components: a laboratory and matrix component. The laboratory component measures the performance of the laboratory analytical process during the sample analyses, while the matrix component measures the effects on the method performance of a specific matrix. Method blanks and laboratory control samples uniquely measure the laboratory component of method performance, while matrix spikes, matrix spike duplicates, laboratory sample duplicates, and surrogate spikes measure the matrix component of method performance, but also reflect laboratory performance. The following paragraphs discuss the QC samples and parameters to be evaluated to assess the overall laboratory data quality.

1.4.5.1. Holding Time

Holding time reflects the length of time that a sample or sample extract remains representative of the environmental conditions. Holding time for method EPA 8021B is 14 days. Analytical results of samples whose holding times are exceeded are considered quantitatively questionable and may be biased low.

1.4.5.2. Duplicate and Replicate Samples

Like the field procedures, the analytical procedures will be evaluated by comparing the analytical results of duplicate or replicate sample pairs. If the reported values for the sample pair are similar, the samples are considered to be representative of the environment. A large difference (greater than 40 percent) between the reported values for the sample pair indicates that there may have been a problem during the sampling or analysis. Duplicate analyses will be used to evaluate precision by calculating the RPD between a duplicate sample and its associated environment sample. The RPD will be compared to the MS/MSD QC limits for precision. Relative percent difference values within the QC guidelines indicate that good sampling and analytical procedures were followed. Relative percent difference values outside the QC limits indicate that sample may be heterogeneous, or that there may have been a problem during sampling and/or analysis.

1.4.5.3. Method Blanks

Method blanks will be used to evaluate representativeness by identifying any contaminants that have been introduced during analysis. Method blanks are generated in the laboratory and consist of ultra-pure water. Method blanks are carried through each processing step necessary for an analytical procedure and are analyzed at frequency of one per 20 samples or daily, whichever is more frequent. These blanks measure contamination originating from the laboratory (i.e., water, air, reagents, equipment, and instruments used for analysis), and help in distinguishing low-level field contamination from laboratory contamination. If analytes of interest are found in both the method blank and associated environmental samples, the environmental data will be qualified as per USEPA guidelines (USEPA, 1988b). The data from the associated samples may be considered quantitatively questionable depending on the relative concentrations of contaminants in the method blank and the environmental sample.

1.4.5.4. Laboratory Control Samples

Laboratory control samples (LCS) will be used to evaluate accuracy. These samples are carried through the same analytical procedures as the environmental samples and are used to evaluate method and analytical procedure performance in the absence of matrix interference. Laboratory control samples are prepared in the laboratory and consist of ultra-pure water that is spiked with specific compounds as outlined in the analytical methods. An LCS sample will be prepared and analyzed at a frequency of one per 20 samples, or daily, whichever is more frequent. Accuracy will be evaluated by calculating the percent recovery for each spiked compound and comparing it to the QC limits established by the individual methods. Values within the established QC limits indicate acceptable analytical accuracy. Values outside the QC limits indicate that the data may be questionable.

1.4.5.5. Matrix Spike and Matrix Spike Duplicate Samples

Results of MS/MSD sample analysis will be used to evaluate accuracy and precision. Unlike LCSs, MS/MSD samples are used to assess the influence of the sample matrix (matrix interference) on the analysis. Each MS/MSD sample will be spiked with the compounds specified by the analytical method. To evaluate accuracy, the percent

recovery for each spiked compound will be calculated and compared to the QC limits established by the method. Precision will be evaluated by calculating the RPD between the MS and MSD samples for each spiked analyte. These RPDs will be compared to the QC limits established by laboratory performance. Percent recovery and RPD values within the QC limits indicate acceptable precision and accuracy values outside the QC limits indicate that there may have been a matrix interference during analysis. The laboratory data validation protocol will be based on precision and accuracy measurements from MS/MSDs. Individual compound recoveries will be compared with acceptance limits. If a matrix spike analyte fails acceptance criteria, the MS/MSD will be reanalyzed and a LCS also will be analyzed. For the method to be considered in control, those compounds that failed the matrix spike criteria must be within acceptance limits in the LCS. If, after re-analysis, analytes that failed acceptance criteria in the MS and MSD pass acceptance criteria in the LCS, these analytes may be considered biased due to sample matrix effects.

All samples analyzed or prepared in a process batch without an MS and MSD will, at a minimum, have a method blank and LCS. The environmental samples in this batch will be considered in control if more than 80 percent of the target compounds in the LCS are within acceptance limits.

1.4.6. Corrective Action - Field Program

The field staff will be responsible for documenting and reporting all suspected technical and QA non-conformances, and suspected deficiencies during any field activity. The non-conformances and/or deficiencies will be documented in the field log book and reported to the ARA Principal Investigator. If the problem is associated with field measurements or sampling equipment, the field staff will take the appropriate steps to correct the problem. Typical field procedures to correct problems include the following:

- Repeating the measurement to check for error
- Making sure the meters or instruments are adjusted properly for the ambient conditions, such as temperature
- Checking or replacing batteries
- Recharging batteries
- Recalibrating the instruments
- Replacing the meters or instruments used to measure field parameters
- Stopping work until the problem is corrected (if necessary).

If a non-conformance or problem requires a major adjustment to the field procedures as outlined in the Work Plan (e.g., changing sampling methodology), the Principal Investigator, in conjunction with the QC Coordinator, will be responsible for initiating corrective actions. The Principal Investigator will be responsible for the following:

- Evaluating the reported non-conformance
- Controlling additional work on non-conforming items
- Determining the appropriate corrective actions
- Maintaining a log of all non-conformances and corrective actions

- Ensuring that explanation of non-conformances and corrective actions is included in an appendix of the report scheduled for this investigation.

The AFRL Principal Investigator will ensure that no additional work that is dependent on the non-conforming activity is performed until the appropriate corrective actions are completed.

1.4.7. Corrective Action - Analytical Program

Corrective actions are required whenever unreliable analytical results prevent the quality control criteria as specified by the method or this QAPP from being met. The corrective action that is taken depends on the analysis and the non-conformance.

Corrective actions will be undertaken if one of the following occurs:

- QC data are outside the acceptance windows for precision and accuracy
- Blanks contain contaminants above acceptance levels
- Undesirable trends are detected for spike recoveries (or spike recoveries are outside the QC limits) or RPDs between duplicate analyses are consistently outside QC limits
- There are unusual changes of detection limits during analysis
- Deficiencies are detected during QA audits
- Inquiries concerning data quality are received from AFRL

Corrective actions are primarily handled at the bench level by the analyst who reviews the sample preparation or extraction procedures, and performs the instrument calibration and analysis. If the problem persists or its cause cannot be identified, the matter will be referred to the Laboratory Manager or QC Coordinator for further investigation. Once resolved, full documentation of the corrective action procedure will be filed with the QC Coordinator. A summary of the corrective actions will be included in the final report submitted to ESTCP.

1.5 Demonstration Procedures

The procedures for technology startup, and maintenance are presented in detail in Section 5.2 of this document.

1.6 Calculation of Data Quality Indicators

The calculation of data quality indicators is described in Section 9.4, Calibration Procedures, Quality Control Checks, and Corrective Action, and in Section 9.3, Data Quality Parameters.

1.7 Performance and System Audits

Oversight of team members' field procedures will be the direct responsibility of the AFRL Principal Investigator, who will review all elements of the QAPP to ensure that the objectives of the Work Plan are met. In addition to an initial review, the sampling procedures will be reviewed as the field work progresses so that any necessary modifications can be made.

Internal audits of all team members' field activities (sampling and measurements) will be conducted by the AFRL/MLQ quality control coordinator or the coordinator's designee. The audits will include examining field measurement records, field equipment calibration records, field sampling records, field instrument operation records, sample collection procedures, sample handling and shipping procedures, and chain of custody procedures. Field activities will be audited early in the project to verify that all of the procedures outlined in the Work Plan and QAPP are being followed. Follow-up audits will be conducted to verify that deficiencies have been corrected, and to verify that QA procedures are maintained throughout the project.

In-house and regulatory agency audits of laboratory systems and performance are a regular part of a laboratory QC program and are outlined in the subcontract laboratory's QA/QC plan. The audits consist of a review of the entire laboratory system and at a minimum include: examination of sample receiving, log-in storage, and chain of custody documentation procedures; sample preparation and analysis; and instrumentation procedures. An external audit may be performed by AFRL/MLQ or its designee prior to or during the field work, to verify proper implementation of laboratory procedures and adherence to this QAPP.

1.8 Quality Assurance Reports

All of the analytical data collected during the investigation will be presented in an appendix to the final technical report scheduled for this investigation. The following information will be included in the report:

- Sampling procedures (planned and implemented, problems, and corrective actions)
- Analytical procedures and detection limits
- Analytical data (environmental and QC sample results)
- Results of the data quality evaluation
- Conclusions and recommendations

APPENDIX B

COMPARISON OF HYDRAULIC CONDUCTIVITY DETERMINATIONS IN DIRECT PUSH AND CONVENTIONAL WELLS

APPENDIX B

COMPARISON OF HYDRAULIC CONDUCTIVITY DETERMINATIONS IN

DIRECT PUSH AND CONVENTIONAL WELLS

Conducted for
Naval Facilities Engineering Service Center
1100 23rd Avenue
Port Hueneme, CA 93043

Conducted by

Stephen A. Bartlett and Dr. Gary A. Robbins
Department of Geology and Geophysics
University of Connecticut
Storrs, CT 06269

J. Douglas Mandrick, and Dr. Michael J. Barcelona
Department of Chemistry
Western Michigan University
Kalamazoo, MI 49008

Wes McCall
Geoprobe Systems, Inc.
Salina, KS 67401

Dr. Mark Kram
Naval Facilities and Engineering Service Center
1100 23rd Avenue
Port Hueneme, CA 93043

January 7, 2004

ACKNOWLEDGEMENTS

This study was conducted under a contract with the Department of Defense, Naval Facilities Engineering Service Center at Port Hueneme, California, contract number N47408-03-C-7407.

Stephen Bartlett and Gary Robbins, with assistance by Wes McCall, performed the field testing. The hydraulic conductivity data analysis was performed by Stephen Bartlett. Michael Barcelona, Douglas Mandrick, and Stephen Bartlett performed the statistical analysis. Mark Kram was the NFESC project manager and originally designed and installed the wells used in the study.

The authors wish to thank Dale Lorenza (Intergraph) for his assistance during the field phase of this study and Geoprobe Systems, Inc for the loan of the pneumatic slug test kit.

EXECUTIVE SUMMARY

The main objectives of this research were:

- to perform a systematic comparison of hydraulic conductivity values derived from conventional and direct push wells;
- to evaluate the validity of conducting short duration pneumatic slug tests in high permeable formations; and
- to help develop guidance on well construction and test methods for improving the determination of hydraulic conductivity values from well testing.

To meet these objectives a study was performed from March 9 to 20, 2003 at a preexisting test site at the Naval Facility, Port Hueneme, California. Over 296 pneumatic slug-in and slug-out tests as well as multiple steady and unsteady state pumping tests were performed in 5 different wells types in 15 different wells. The 5 different well types were: 2" diameter conventional hollow stem auger wells, 2" diameter direct push wells with prepacks, two ¾" prepack direct push wells with different types of prepack designs, and ¾" naturally developed prepack wells. The wells were screened between 7 and 17.5 feet in fluvial-deltaic sediments consisting of medium to coarse-grained sand and gravel. The ground water table was relatively shallow from 5 to 7 feet deep and all the screens were fully submerged.

The pertinent conclusions of the study were:

- Short duration pneumatic slug tests were determined to be a viable approach for determining hydraulic conductivity values in a high permeable formation. The results of a statistical comparison between the pneumatic slug tests lasting only a few seconds and the steady state pumping tests yielded no statistical difference.

- Hydraulic conductivity values in direct push wells were found to be independent of prepack design, well radius, induced head, and test method (assuming the same screened interval).
- The hydraulic conductivity values determined from the different well types in the B1 and B2 clusters had a mean post development value of 2 x 10^{-2} cm/sec and a standard deviation of 8 x 10^{-3}. The ANOVA analysis indicated there was no statistical difference amongst the prepack wells. Furthermore, there was no statistical difference between the pushed no pack wells and the drilled wells. However, the ANOVA analysis indicated that there was a statistical difference between the latter wells and the prepack wells. The variance associated with hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells is largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method.
- Although development had an impact on the hydraulic conductivity for most of the wells, the impact was ambiguous. Of the 15 wells tested 10 wells had statistical differences in hydraulic conductivity between pre and post development. Of the 10 wells, 5 wells showed increases in hydraulic conductivities and 5 well showed decreases.
- Unsteady state, steady state pump tests, and pneumatic slug tests were shown to be statistically comparable means of determining hydraulic conductivity analysis in high permeable formations.

The following is additional guidance to improve pneumatic slug testing in high permeable environments.

- Three or more tests should be done at any given well to determine reproducibility;
- Attention should be paid to proper well design (especially having the screened section fully submerged during testing) and rigorous well development;
- Care must be taken in choosing the appropriate portion of the log head versus time curve for analysis;
- High frequency data acquisition pressure transducers should be used in conducting tests in highly permeable wells;
- Use of vacuum-pressure pumps permits conducting slug-in, in addition to slug-out tests in a very controlled, highly reproducible manner; and
- Spreadsheet templates should be developed to aid in data management and analysis.

Based on the results of this study, the following are recommendations for future research to improve slug test methods and to evaluate differences in hydraulic conductivities determined in different well types:

- Ideally the comparative tests conducted here would have been enhanced if there were more well clusters all screened over the same depth interval. This would help reduce ambiguities, increase the data for statistical analysis, and permit an assessment of the degree of spatial heterogeneity by examining how the hydraulic conductivities vary for a given well type.

- It would also be valuable to have wells developed and tested immediately following installation.
- To examine the impact of scale on the determination of the hydraulic conductivity value, two well steady state pumping tests should be conducted. For example, using one well as the pumping well and having multiple observation wells at different distances, one can evaluate how the hydraulic conductivity varies spatially and with distance for comparison to the slug test results.
- It would be useful to conduct testing at several locations having widely different hydraulic conductivities. These tests would help evaluate the extent to which hydraulic conductivity values determined in wells in different formation types are sensitive to well installation and development.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	ii
EXECUTIVE SUMMARY	iii
TABLE OF CONTENTS	vii
LIST OF FIGURES	x
LIST OF TABLES	xiii
LIST OF SYMBOLS	xiv
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Factors Affecting Slug Test Results	4
1.3 Problem Statement	6
1.4 Study Objectives	6
2.0 TEST SITE DESCRIPTION	8
3.0 EXPERIMENTAL METHODOLOGY	11
3.1 Slug-in and Slug-out Test Equipment	11
3.2 Pump Test Equipment	15
3.3 Development Equipment	17
3.4 Test Procedures	18
3.4.1 Slug Test - Pre Development	19
3.4.2 Slug Test - During Development	23
3.4.3 Slug Test - Post Development	23
3.4.4 Pumping Tests	24

3.4.5 Tests for Spatial Heterogeneity 26

3.5 Hydraulic Conductivity Analysis 26

3.5.1 Slug In/Out Hydraulic Conductivity Analysis 27

3.5.2 Steady State One & Two Well Tests 36

3.5.3 One Well Unsteady State Tests 39

3.6 Statistical Analyses 41

3.6.1 Analysis of Variance (ANOVA) 41

4.0 RESULTS 44

4.1 Tally of Tests Performed 44

4.2 Individual Well Issues 45

4.2.1 Pre, During, and Post Development Hydraulic Conductivity Comparison 45

4.2.2 Induced Head Change Comparison 46

4.2.3 Slug In/Out Hydraulic Conductivity Value Comparison 47

4.3 Issues Relating to Well Depth, Location, and Type 48

4.3.1 Screen Length Comparison 48

4.3.2 Comparison Between P1 Wells 49

4.3.3 Comparison Between Direct Push Well Types 50

4.3.4 Direct Push Wells vs. Conventional Wells 52

4.4 Issues Relating to Test Method 56

4.5 Well Construction Parameter Sensitivity Analysis 59

5.0 DISCUSSION 62

5.1 Interpretation of Test Results 62

5.1.1 Log Head vs. Time Slopes 62

5.1.2 Influence of Induced Head on Hydraulic Conductivity 63

5.1.3 Comparison of Hydraulic Conductivity Values Determined by Slug-in and Slug-out Tests 64

5.1.4 Comparison of Hydraulic Conductivity Values Determined from Wells with Different Screen Lengths 64

5.1.5 Comparison of Hydraulic Conductivities Values Determined from Prepack Wells 65

5.1.6 Comparison Between Naturally Developed and Prepack Wells 65

5.1.7 Comparison Between Pushed and Drilled Wells 67

5.1.8 Comparison Between Pushed and Drilled Wells 67

5.1.9 Deviations of Head Recovery Curves from Ideality 69

5.2 Sources of Error in the Hydraulic Conductivity Tests 73

5.2.1 Propagation of Error 75

5.3 Comparison of Test Results to Previous Studies 75

5.4 Applicability of Findings 80

5.5 Recommendations for Future Research 82

6.0 CONCLUSIONS 84

REFERENCES 86

APPENDICES

Appendix A – Propagation of Error Calculation 90

Appendix B - Spreadsheet Summary of Hydraulic Conductivity Tests CD

Appendix C - Slug Test Analyses CD

Appendix D - Pump Test Analyses CD

An accompanying CD ROM includes the Geoprobe raw data files, analysis spreadsheets, and AQTESOLV analyses.

LIST OF FIGURES

Figure 2-1. Site Map (Kram, 2001) 8

Figure 2-2. Cell B Layout (Kram, 2001) 10

Figure 2-3. Three Dimensional Cell B Layout (Kram, 2001) 10

Figure 3-1. Original Geoprobe Pneumatic Slug Test Kit Configuration (Geoprobe Website) 11

Figure 3-2. Drawing of Pneumatic Slug Test Kit Manifold Assembly (Geoprobe Website) 12

Figure 3-3. Geoprobe Pressure Transducer 12

Figure 3-4. Brailesford TD-2 Single Head Pressure/Vacuum Pump 13

Figure 3-5. Modified Geoprobe Pneumatic Slug Test Kit, capable of performing slug out/ slug in tests. 14

Figure 3-6. Schematic of the Modified Geoprobe Pneumatic Slug Test Kit in Slug-Out Mode 14

Figure 3-7. Modified Geoprobe® Pneumatic Slug Test Kit, capable of performing slug-in air vacuum tests 15

Figure 3-8 Schematic of the Modified Geoprobe Pneumatic Slug Test in Slug-in Mode 15

Figure 3-9. Master Flex ES Portable Sampler, Cole Palmer, Model 7518-02 (left) and Master Flex, Cole Palmer, Model 7549-32 (right) 16

Figure 3-10. In-Situ Pressure Transducer 16

Figure 3-11. Surge block tool showing from top to bottom the 2” surge plunger, ¾” plunger, and pressure release valve 17

Figure 3-12. Orbeco-Hellige Model 966 Portable Turbidimeter 18

Figure 3-13. Pump Test Setup 25

Figure 3-14. Drawing of Pump Test Configuration 25

LIST OF FIGURES (cont.)

Figure 3-15. Geoprobe ASCII Data File 27

Figure 3-16. Pressure Transducer Reading (ft) vs. Time (s) 28

Figure 3-17. Time vs. Log (Head) Output 29

Figure 3-18. Log Linear Portion of Graph Analyzed 30

Figure 3-19. Data Analysis Output 30

Figure 3-20. High Hydraulic Conductivity Estimator Spreadsheet (Butler, 2000) 32

Figure 3-21. Chart 2, Pressure Head (ft) vs. Time (s) 33

Figure 3-22. Chart 3, Curve Matching 33

Figure 3-23. Sheet 1, Type Curve Generator Spreadsheet 35

Figure 3-24. Chart 1, C_D Type Curve 35

Figure 3-25. Sheet 2, Hydraulic Conductivity Calculator 36

Figure 3-26. Single Well Steady State Pumping Test Analysis Sheet 37

Figure 3-27. Discharge vs. Head from Steady State Pump Test Data 38

Figure 3-28. Two Well Steady State Thiem Analysis Sheet 39

Figure 3-29. AQTESOLV Analysis 40

Figure 3-30. Whisker-Box Plot Diagram 43

Figure 4-1. Result Comparison by Test Method 45

Figure 4-2. Induced Head Comparison 47

Figure 4-3. Slug in vs. Slug out Comparison 48

Figure 4-4. Screen Length Comparison 49

Figure 4-5. Variation of Hydraulic Conductivity with Depth in the P1 Wells 50

Figure 4-6. Prepack Slug Test Hydraulic Conductivity Comparison 51

LIST OF FIGURES (cont.)

Figure 4-7. Direct Push Well Type Hydraulic Conductivity Comparison 52

Figure 4-8. Pushed (P) vs. Drilled (D) Wells Hydraulic Conductivity Comparison (Slug Data) 53

Figure 4-9. Pushed (P) vs. Drilled (D) Wells Hydraulic Conductivity Comparison (Steady State Data) 54

Figure 4-10. Drilled (d) vs. Pushed No Pack (pnp) Hydraulic Conductivity Comparison 55

Figure 4-11. Slug Test Well Type Hydraulic Conductivity Comparison 56

Figure 4-12. Slug, Steady State, Unsteady State Hydraulic Conductivity Comparison 57

Figure 4-13. Steady State K Value Data Set vs. Slug Test K Value Data Set by Well Type. 58

Figure 4-14. Hydraulic Conductivity Comparison between 1 and 2 Well Steady State Pumping Tests 59

Figure 5-1. Ideal Head vs. Time Recovery Curve (Well B1-1, Post Development) 69

Figure 5-2. Momentary Delay in Recovery (B1-3 Post Development) 70

Figure 5-3. Double Straight Line Recovery (B2-2 Post Development) 71

Figure 5-4. Oscillation Before Recovery (B2-2 Post Development) 72

Figure 5-5. Oscillatory Recovery (Well B4-6) 73

Figure 5-6. Slug in vs. Pneumatic Test Hydraulic Conductivity Comparison 76

Figure 5-7. Hydraulic Conductivity Comparison of Traditional Slug-in and Pneumatic Vacuum Slug in Tests 77

LIST OF TABLES

Table 2-1. Well Type Description 9

Table 3-1. Test Matrix 19

Table 4-1. Test Completion Table 44

Table 4-2. Development Impact 46

Table 4-3. Slug vs. Steady State Hydraulic Conductivity Comparisons 58

Table 4-4. Drilled Well Sensitivity Analysis. 60

Table 4-5. Pushed No Pack Sensitivity Analysis 61

Table 5-1. Summary of ANOVA Results 62

Table 5-2. Slug Test Duration Summary Statistics (seconds) 68

LIST OF SYMBOLS

ANOVA	analysis of variance
bgs	below grade surface
CPT	cone penetrometer
D	2” ID, hollow stem auger, ASTM Design, Tremmied
ft	feet
HSA	hollow stem auger
Hz	hertz
ID / OD	inner diameter / outer diameter
K	hydraulic conductivity
L/min	liters/minute
ml/min	milliliters/minute
MTBE	Methyl Tertiary Butyl Ether
NBVC	Naval Base Ventura County
NFESC	Naval Facilities Engineering Service Center
P	2” ID, Pushed, ASTM Design Prepack
P1	¾” ID, Pushed, ASTM Design Prepack
PCV	¾” ID, Pushed, Conventional Design Prepack
PNP	¾” ID, Pushed, Pushed No Filter Pack
s	seconds
v	voltage

1.0 Introduction

1.1 Background

The hydraulic conductivity of a formation is a critical site characterization factor needed in determining groundwater velocity and discharge, performing assessments of contaminant transport rate and direction, designing remedial systems, and for performing risk assessment. Determining hydraulic conductivity values in a three dimensional hydrogeologic framework is critical in arriving at an effective remediation strategy.

Slug tests are the most widely used method for field determination of hydraulic conductivity at contamination sites (Butler, 1996; Henebry and Robbins, 2000). Slug tests are one-well tests that entail the instantaneous addition or removal of a slug of water from a well (Hvorslev, 1951). They are advantageous because they can be performed by one person, they are simple to run, they take only minutes to a few hours to conduct, and they entail relatively uncomplicated analysis (Butler, 1998). Furthermore, unlike a pumping test, little water must be disposed of which is a significant concern at contamination sites. Slug tests may be performed by pouring water into a well (slug-in) or bailing water out of a well (slug-out) to change the static water level. A slug-out test can also be performed by displacing a known volume of water using a mandrel (Hvorslev, 1951, Henebry and Robbins, 2000). Following the initial change in static water level, the water level recovery in the well is monitored with time. The water level-time recovery curve is then used in an analytical model that describes how the water level changes with time as a function of well geometry, formation geometry, and hydraulic conductivity (Hvorslev, 1951; Bower and Rice, 1976). By substituting recovery curve

data, formation, and well geometry parameters into the model the hydraulic conductivity can then be calculated (ASTM, 1996).

The introduction of slug test analysis began in 1951 when M. Juul Hvorslev of the Army Corps of Engineers compiled formulas for the determination of subsurface water flow through different well intake types and developed the time lag method for determining hydraulic conductivity (Hvorslev, 1951). Though the means by which slug tests are conducted have changed, Hvorslev's equations are still used to calculate hydraulic conductivity.

Ferris and Knowles (1954) coined the term "slug test" and devised the general method used to perform these tests in fully penetrating wells in confined aquifers. Later, Bouwer and Rice (1976) developed equations for partially and completely penetrating wells in unconfined aquifers.

In the past, slug tests were generally confined to formations having hydraulic conductivities less than 10^{-4} cm/s. In highly permeable sediments, standard slug tests could not be performed because of the near instantaneous water level recovery following displacement. More recently, slug tests have been conducted in high hydraulic conductivity formations using pneumatic systems (Leap, 1984, Butler et al., 2002a) and vacuum systems (Orient et al, 1987) to induce the water level change along with pressure transducers that permit high-speed data acquisition (Butler et al., 2002b).

Prosser (1981) devised a pneumatic system in which the hydraulic conductivity was determined by injecting an air pressure slug into the well. Instead of introducing a solid object into the well he found that air pressure (like the solid object) would displace water. Having achieved a new equilibrium the pressure was then released and the water

table returned to static. With water level response measured by electronic pressure transducers, slug tests could now be conducted in aquifers with higher hydraulic conductivity whereas before traditional sounders could not record fast enough because of the quick water table recovery (Prosser, 1981). Leap (1984) published a paper describing a “simple pneumatic device.” His device injected compressed air into the well through a sealed device called a wellhead manifold. This paper described the setup, operation, and slug test method of analysis especially in small diameter wells, where normal test methods prove unsuccessful. Orient et al. (1987) further developed the air pressure pneumatic system and modified it in order to perform slug tests using a vacuum system. Instead of pressurizing the well casing and lowering the water table the water table could be drawn up and then released. This is akin to a slug-in test with a given volume of water. McLane et al (1990) constructed a pneumatic apparatus capable of conducting both slug-in and slug-out tests in highly permeable aquifers.

Often slug tests conducted in high permeable environments exhibit inertial oscillations, which complicate the analysis. Van der Kamp (1976) provided a method for determining the hydraulic conductivity from a slug test in a well exhibiting inertial oscillations. The inertial action is much like what is observed when a spring is pulled and released and it oscillates before returning to a static state. In a well bore this problem results after inducing a head when the formation has a high permeability. Because the water can recover rapidly, the water enters the well at such a rate that it overshoots the static water level and sets up an oscillation in the well bore. Because of the short recovery duration, the oscillation dominates the entire period of recovery. Van der Kamp (1976) developed a theoretical solution for analyzing an oscillatory recovery to determine

the hydraulic conductivity. Subsequently other models for the oscillatory case for different well geometries and formation conditions developed (Kipp, 1985; Spring and Gelhar, 1991; Butler, 1997; McElwee and Zenner, 1998). Butler and Garnett (2000) subsequently derived an alternative means for analyzing the oscillatory data and a method of analysis using a Microsoft Excel spreadsheet. Butler (2002) subsequently developed a method to correct for frictional loss when analyzing oscillatory data in small diameter wells in high hydraulic conductivity aquifers.

In 2001, Geoprobe® Systems, Inc. began manufacturing the GW1600 Geoprobe® Pneumatic Slug Test Kit designed to perform pressurization slug-out tests in unconsolidated soils or sediments. The kit, which contains the necessary equipment, pressure transducer, and computer software, was the source of slug test data for our research effort.

1.2 Factors Affecting Slug Test Results

The value of hydraulic conductivity derived from slug tests may be influenced by a number of factors. These include:

- the soil type;
- the degree of formation heterogeneity;
- the static water level relative to the intake;
- the model used;
- well design geometry parameters chosen (includes casing ID, intake radius, intake length, radius of influence (when applicable) and correction factors);
- drilling method and associated formation disturbance(e.g. compaction or loosening of the soil);

- intake clogging caused during well installation;
- well intake efficiency and frictional effects;
- the magnitude of the slug as it impacts the effective stress (resulting in formation expansion or contraction);
- the duration of the test;
- and random errors associated with water level and time measurements (Binkhorst and Robbins, 1994; Binkhorst and Robbins, 1998; Henebry and Robbins, 2000; Butler, 2002)

Conventional monitoring wells have traditionally been used to conduct slug tests. Typically, these wells are installed using hollow stem auger drilling. The 2” diameter wells are installed in oversized boreholes with sand packs surrounding the screen sections (ASTM, 1990). More recently, as emphasis increases in evaluating the three-dimensional nature of contaminant plumes, short screened (6” to 5’), small diameter (1/2” and 3/4”), monitoring wells are being installed using direct push methods (ASTM, 2001a). Direct push refers to the method by which a well is inserted by pushing or hammering drive points and rods into the ground with hydraulic rams and hammers mounted on vehicles (e.g., Geoprobe® Systems machines, cone penetrometer technology (CPT) trucks). These wells may be naturally developed (no sand pack) or constructed using sand packs. Sand packs may be either tremmied into the hole around the well screen or may be fashioned to the well screen as a prepack. Prepacks consist of sand incorporated in a wire screen mesh that is clamped to the well screen and is inserted into the hole with the well casing (ASTM, 2001b).

A critical point of concern is the potential well design bias that may affect the reliability of hydraulic conductivity values obtained in testing drilled hollow stem auger wells and direct push wells. Hollow stem auger wells are installed in holes that are drilled with large diameter auger flights that screw into the soil. The action of the drill bit and flights may cause loosening of the soil directly adjacent to the hole resulting in increasing the near-field hydraulic conductivity. Loosened fines may also clog the formation near the hole decreasing the hydraulic conductivity. Direct pushed wells are installed in holes that have been made by hammering and pushing rods into the ground. Drill rod pounding or pushing can cause soil compaction and lower hydraulic conductivities in the adjacent formation materials.

1.3 Problem Statement

Given the differences between the installation and construction of conventional wells and direct push wells, the question arises as to whether hydraulic conductivity values derived from these wells differ. Furthermore, one may raise the question as to which well type provides a more accurate determination of hydraulic conductivity.

1.4 Study Objectives

The objectives of this research were: (1) to perform a systematic comparison of hydraulic conductivity values derived from conventional and direct push wells; (2) to ascertain, if differences are found, as to the underlying reasons (bias) for these differences, and (3) if differences in conductivity values exhibit systematic bias, to attempt to develop a consistent factor or formulation to compensate for potential differences in hydraulic conductivity values derived from different types of wells. This in turn was used to help develop guidance on well construction and test methods for

accurately determining the hydraulic conductivity especially for those who use direct push wells.

2.0 Test Site Description

The field tests for this study were conducted at an existing well field at the Naval Base Ventura County (NBVC), Port Hueneme, California. The well field had been installed as part of a study to compare water quality parameters obtained from sampling different well types (Kram et al., 2001). The well field is located at the down gradient end of a 4575 ft MTBE plume (Figure 2-1).

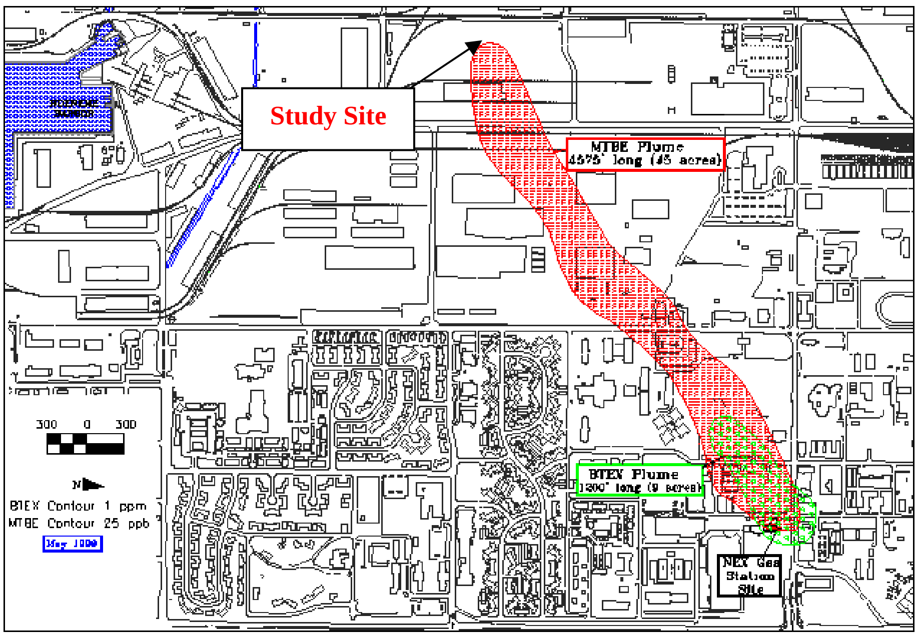


Figure 2-1. Site Map (Kram, 2001)

The site area is underlain by approximately 328 ft (100 m) of unconsolidated Holocene age sediments, composed of three depositional layers ranging from an upper clayey fill layer at the surface to 9.8 ft (3m) below ground surface (BGS), a fine to medium-grained sand from 9.8 ft (3m) to 19.7 ft (6m) BGS, and a clayey layer beginning at 19.7 ft (6m) (Salanitro, 2000). Kram (2001) describes the test site stratigraphy in detail. The wells are installed in a “semi-perched” aquifer zone consisting of fluvial-deltaic sediments to a depth of approximately 25 feet (4.6 m). Based on soil coring and

CPT logging the stratigraphy in the immediate vicinity of the test site consists of the following: interbedded silt, sand, and clay from the surface to approximately 7 ft (2.1 m); medium sand from 7 to 12 ft (2.1 to 3.7 m); coarse sand/gravel from 12 to 18 ft (3.7 to 5.5 m); and clay from 18 to 25 ft (5.5 to 7.6 m).

Ground water flow in the semi-perched aquifer zone is to the southwest. Salinitro et al (2000) reported that the hydraulic gradient in the MTBE plume vicinity ranged from 0.001 to 0.003. The hydraulic conductivity at an up gradient test site was found to range from $5x10^{-3}$ cm/s to $8x10^{-3}$ cm/s for wells with screened intervals ranging from 9.8 ft (4.5 m) to 19.7 ft (6 m) (Salanitro et al., 2000). During the test period the unconfined water table typically ranged from 5 to 7 feet (1.5 to 2.1 m) bgs.

The well field "Cell B" consisted of four well clusters installed in a parking lot west of Building 401 (Figure 2-2). Each well cluster is screened over a different depth interval (Figure 2-3). Within each well cluster were five different well types (Table 2-1). The prepacks were designed by GeoInsight, Inc. The pcv well type represents an off-the-shelf conventional design, whereas the prepacks for the p1 and p well types were designed for this site based on grain size analyses and ASTM procedures (Kram, 2001) For this study, the majority of testing was conducted in Cell B, Clusters 1 and 2.

Type	Construction
pnp	3/4" ID, Pushed No Filter Pack (#10 slot)
p1	3/4" ID, Pushed ASTM Design Prepack (#20 slot, 10-20 Mesh sand)
pcv	3/4" ID, Pushed Conventional Design Prepack (#10 slot, 20-40 Mesh sand)
p	2" ID Pushed ASTM Design Prepack (#20 slot, 10-20 Mesh sand)
d	2" ID "HSA", ASTM Design, Tremmied (#20 slot, 10-20 Mesh sand)

Table 2-1. Well Type Description

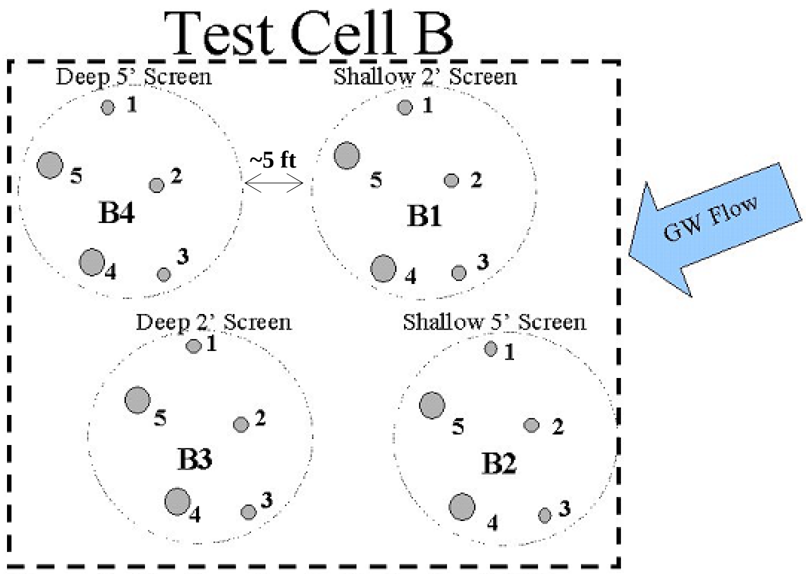


Figure 2-2. Cell B Layout (Kram, 2001).

Cluster	Screen Length	Screen Interval
B1	2 ft.	10 to 12 ft.
B2	5 ft.	7 to 12 ft.
B3	2 ft.	16 to 18 ft.
B4	5 ft	12.5 to 17.5 ft.

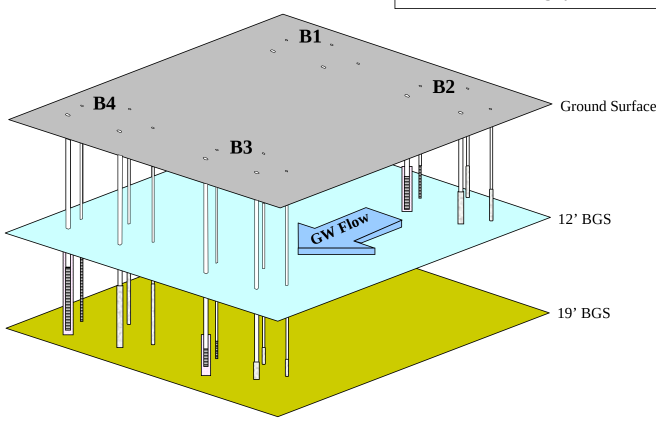


Figure 2-3. Three Dimensional Cell B Layout (Kram, 2001)

3.0 Experimental Methodology

Pneumatic slug tests (slug in and out) and pumping tests (single and double well) were conducted at the site to determine hydraulic conductivity values. The equipment used to conduct tests is described in this section.

3.1 Slug-in and Slug-out Equipment

Pneumatic slug tests were conducted using a modified version of the GW1600 Geoprobe® Pneumatic Slug Test Kit. The Geoprobe® Slug Test Kit consists of a pressure transducer, manifold assembly, data acquisition device (logger), and software accessories for conducting slug-out tests (Figures 3-1 to 3-3). Figure 3-1 provides a setup schematic and Figure 3-2 shows the components of the manifold assembly. The pressure transducer (Figure 3-3) and the software allow data acquisition at variable frequencies up to 38 Hz. This high frequency data acquisition is key to conducting slug tests in high permeable formations such as those found at the test site.

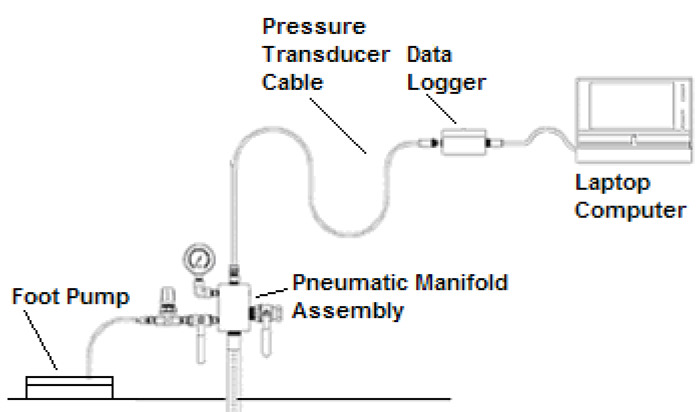


Figure 3-1. Original Geoprobe® Pneumatic Slug Test Kit Configuration (Geoprobe® Website)

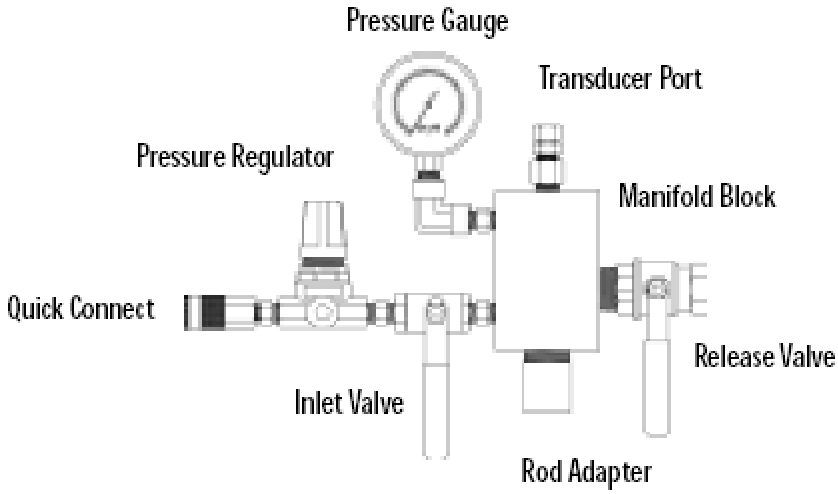


Figure 3-2. Drawing of Pneumatic Slug Test Kit Manifold Assembly (Geoprobe® Website)

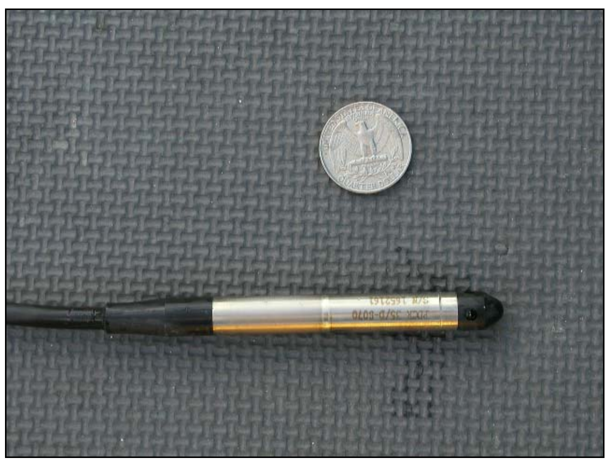


Figure 3-3. Geoprobe® Pressure Transducer

The original pneumatic system was modified to help improve reproducibility and to perform slug-in tests. The foot pump supplied with the system was replaced with a Brailesford pressure/vacuum pump to increase control over induced pressure and vacuum used in testing (Figure 3-4).

Figure 3-4. Brailesford TD-2 Single Head Pressure/Vacuum Pump

The original manifold was modified by the addition of several components (Figure 3-5 – 3-8). A Nupro ball valve was added using Swagelok™ fittings between the manifold block and the pressure gage to isolate the pressure gage during vacuum testing. Attached to the inlet valve was a 1 ½ in. brass nipple, connected to a three-way Whitey ball valve, which served to separate the system between slug-in and slug-out components. On the slug-out side of the Whitey ball valve was the Geoprobe® pressure regulator, which attached to the Brailesford pump. On the other side of the Whitey ball valve was a Nupro ball valve and a tubing connector. The tubing connector served as the connection point to the new vacuum assembly. At the vacuum assembly a Swagelok™ tee split to a Dwyer Magnehelic Gage Model 2100 C, 0 - 100 inches of water for measuring the headspace vacuum. The other branch of the tee connected to a Nupro ball valve to isolate the system for leak testing, a Nupro precision valve used to regulate the vacuum, and a Whitey ball valve to serve as the vacuum cut off, which then was connected to the

vacuum side of the Brailesford pump using polyethylene and Tygon tubing (Figure 3-7 and 3-8).

Figure 3-5. Modified Geoprobe® Pneumatic Slug Test Kit, capable of performing slug out/ slug in tests.

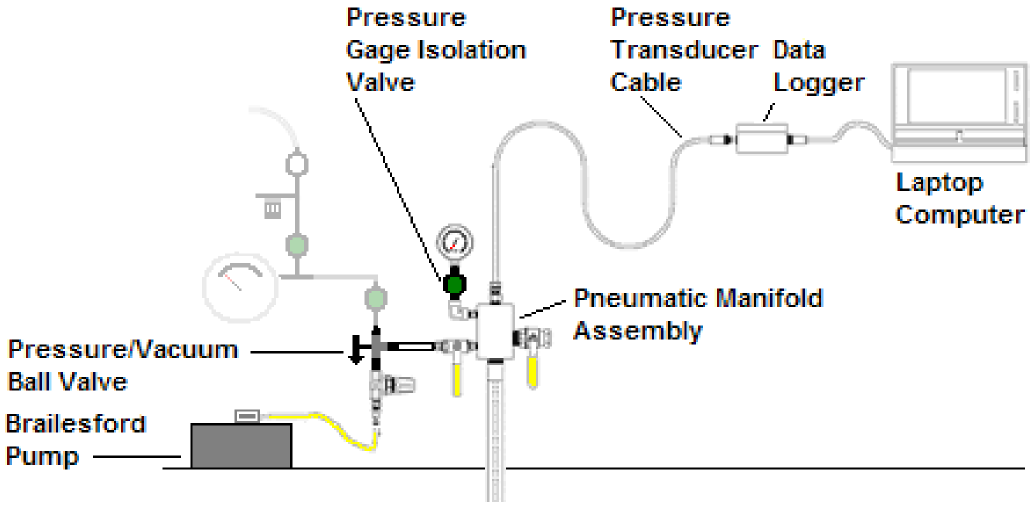


Figure 3-6. Schematic of the Modified Geoprobe® Pneumatic Slug Test Kit in Slug-Out Mode

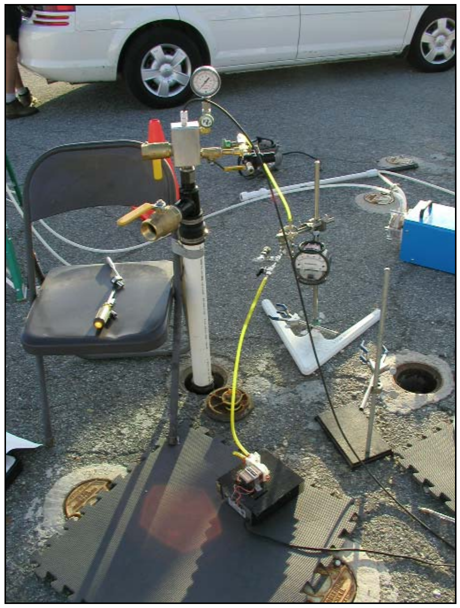


Figure 3-7. Modified Geoprobe® Pneumatic Slug Test Kit, capable of performing slug-in air vacuum tests

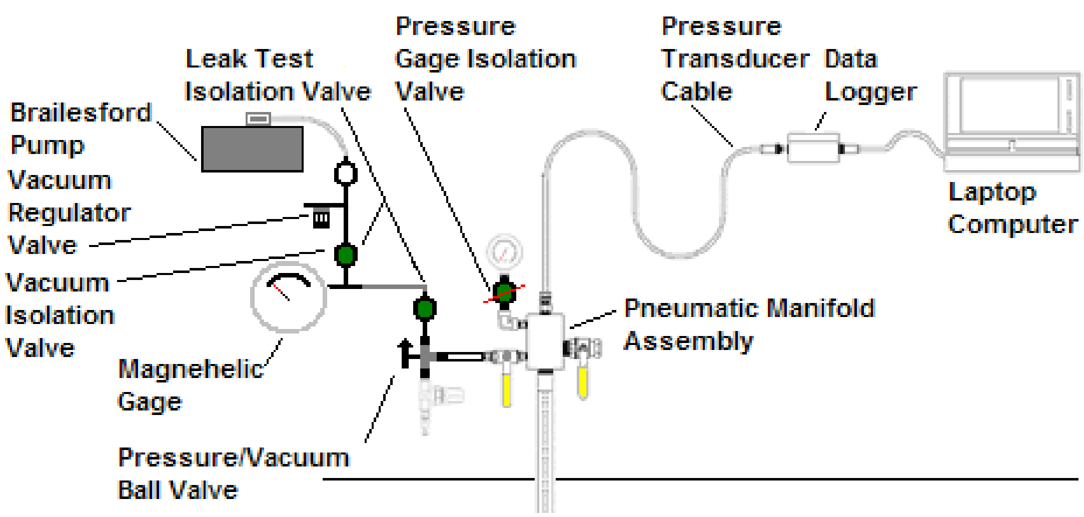


Figure 3-8. Schematic of the Modified Geoprobe® Pneumatic Slug Test in Slug-in Mode

3.2 Pump Test Equipment

Pumping tests were conducted using two peristaltic pumps to obtain a range of discharge rates (Figure 3-9). Pumps were connected to ½” or ¼” OD polyethylene tubing depending on the flow rate. The rates were measured volumetrically using a stopwatch

and graduated cylinders. The water obtained from pump tests and development was discharged to 55-gal drums for appropriate disposal.

Figure 3-9. Master Flex ES Portable Sampler, Cole Palmer, Model 7518-02 (left) and Master Flex, Cole Palmer, Model 7549-32 (right)

The pressure transducer from the Pneumatic Slug Kit was used in pumping wells while a In-Situ MiniTroll Gage Pressure Transducer was used in observation wells (Figure 3-10). Both pressure transducers were connected to separate laptop computers in the field.

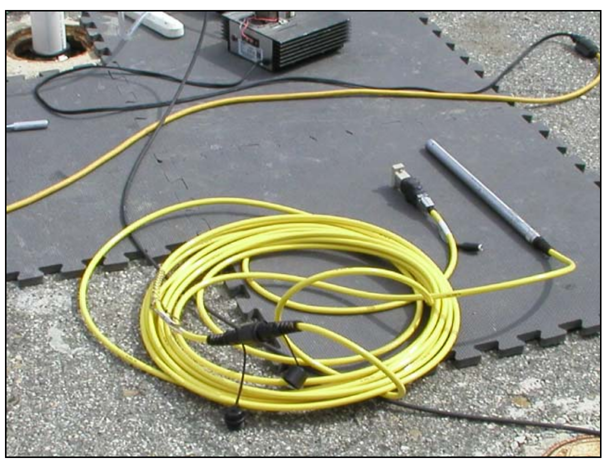


Figure 3-10. In-Situ Pressure Transducer

3.3 Development Equipment

Well development was performed using a surge block technique developed by Robbins and Henebry (2000). Figure 3-11 shows the essential components of the surge block tool.

Figure 3-11. Surge block tool showing from top to bottom the 2” surge plunger, ¾” plunger, and pressure release valve

For the 2” diameter well the surge block consisted of components from an expandable well cap. For the ¾” diameter well the surge block consisted of a septum from a 40 ml VOA vial. Each surge block, depending on the well diameter, was connected to a 3” long, ½” OD threaded lamp screw that coupled to a 4’ length of a ½” aluminum pipe. Four-foot sections of aluminum pipe were coupled together to extend the surge block to the bottom of a well, as needed. A pressure release valve was coupled to the aluminum pipe also by means of a ½” OD threaded lamp screw.

Turbidity measurements were taken using the Orbeco-Hellige Model 966 Portable Turbidimeter (Figure 3-12). This turbidity meter was capable of determining nephelemetric turbidity units (NTUs) in the range of 0 to 999 NTUs.

Figure 3-12. Orbeco-Hellige Model 966 Portable Turbidimeter

3.4 Test Procedures

Table 3-1 provides a matrix of the tests performed. In total, 296 tests were performed in 13 days. The table below gives a break down of the specific number of each test type. Only the “p1” wells were tested in clusters B3 and B4 (3 wells) in order to ascertain the magnitude of variance that may be caused by heterogeneity.

Table 3-1. Test Matrix

Well Type: pnp = pushed no pack, p1= 1" pushed well, pcv =pushed conventional, p = pushed, d = drilled

Test Objective: D = Development, H = Heterogeneity, C = Comparison, B = Bias

Test Number:						Pre Development			Development			Post Development	Higher Head I	Higher Head II			Constant Head Pumping Test			Unsteady State Pumping Test
Cluster B1 2ft Screen 10 to 12ft				1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Well Cluster	Cell Number	Well Number	Well Type												rate 1	rate 2	rate 3	rate 1	rate 2	rate 3
B	1	1	pnp	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	1	2	p1	D	D	D	D	D	D	C,H	C,H	C,H	B	B	B	B	B	H	H	H
B	1	3	pcv	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	1	4	p	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	1	5	d	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	1	6	p1	D	D	D	D	D	D	C,H	C,H	C,H	B	B	B	B	B	H	H	H
B	1	7	d	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
Cluster B2 5ft Screen 7 to 12ft																				
B	2	1	pnp	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	2	2	p1	D	D	D	D	D	D	C,H	C,H	C,H	B	B	B	B	B	H	H	H
B	2	3	pcv	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	2	4	p	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
B	2	5	d	D	D	D	D	D	D	C	C	C	B	B	B	B	B	H	H	H
Cluster B3 2ft Screen 16 to18ft																				
B	3	1	pnp																	
B	3	2	p1	D	D	D	D	D	D	H	H	H	B	B						
B	3	3	pcv																	
B	3	4	p																	
B	3	5	d																	
Cluster B4 5ft Screen 12.5 to18ft																				
B	4	1	pnp																	
B	4	2	p1	D	D	D	D	D	D	H	H	H	B	B						
B	4	3	pcv																	
B	4	4	p																	
B	4	5	d																	
B	4	6	p1	D	D	D	D	D	D	H	H	H	B	B	B	B	B	H	H	H
B	4	7	d																	

3.4.1 Slug Test - Pre Development

Prior to conducting any testing water level measurements were taken and the appropriate well log was consulted (Table 3-1, Column 1,2,3). In order to ensure that the

screened section of the well was not dewatered during a slug-out test the following calculation was made:

Maximum Allowable Induced Head (Slug-Out Test) must be < Depth to Screen (bgs) – Depth to Water (bgs) (3-1)

For example, if the screen was 12 ft from the surface and the water table was 7 ft one would not induce a head larger than approximately 4.5 ft. If the water table was dropped below the screened section, air would be pressurized into the formation and the test would be impacted. If a desired head change was not attainable by a slug-out test because of the potential for screen dewatering a slug-in was performed instead.

In order to evaluate how development may impact hydraulic conductivity values wells were tested prior to development. All the wells in clusters B1 and B2 and the “p1” wells in clusters B3 and B4 were tested in triplicate before development (Table 3-1, tests 1, 2 and 3). Prior to the tests, the water in the wells was agitated and turbidity measurements were taken. Based on a review of the water quality data from the test site (Kram et al., 2001), there was very little variation in field water quality parameters (EC, temperature, pH, Ep, and DO) with depth. Therefore, these parameters were not used to verify that the depth intervals of testing were approximately the same amongst the wells.

The following is a brief synopsis of how the Geoprobe® Pneumatic Slug Test System was setup along with the modifications made to the system (Figure 3-6, Figure 3-8). For more information on the setup, see the Geoprobe® System Pneumatic Slug Test Standard Operating Procedure Technical Bulletin (Geoprobe®, 2002). The pneumatic manifold assembly is available with different adapters that permit it to be sealed on wells with different casing diameters. With the manifold in place, the pressure transducer was inserted through the top port of the pneumatic manifold assembly and into the well.

Based on a maximum drawdown of 3 feet the pressure transducer was typically set at approximately 4 feet below the static water table in all tests performed. The pressure transducer was connected to the data logger, and the data logger to the laptop computer.

Once the test kit system is assembled and prior to it being connected to a well a leak test was conducted on the pressure and vacuum sides of the system. To ensure an airtight seal between the pneumatic manifold and the well casing often required the top of the well casing to be filed smooth and the O-ring seals in the adapter to be coated with silicon grease.

After the adapter was sealed on the well, the pressure transducer was lowered through the manifold assembly in to the water in the well to thermally equilibrate. Thermal equilibration was monitored on the laptop by observing the voltage output of the pressure transducer. When the voltage output was constant the pressure transducer was pulled up slightly above the water level in the well and zeroed in the wellhead space. After zeroing the pressure transducer it was lowered back into the water. Using Teflon tape to ensure an airtight seal, the pressure transducer was sealed into the top of the manifold assembly with a compression fitting.

If a slug-out test was performed the following procedure was followed. The vacuum side of the system was isolated using the Whitey ball valve. The Brailesford pump was connected to the Geoprobe® pressure regulator quick-connnect. The pump was turned on and the regulator throttled until the desired pressure head was attained on the pressure gage. When the pump was turned on, the pressure transducer showed a pressure increase in the wellhead. The transducer was then monitored until the pressure returned to the starting pressure reading. The inlet valve was then closed isolating the

wellhead from the pump. The pressure gage on the manifold assembly was monitored to ensure that the pressure was stable and there was no leakage. To initiate the test the release valve was opened. The pneumatic manifold assembly includes two different sized release valves. The larger valve was used when testing the 2” wells and the smaller valve when testing the ¾” wells. Upon opening the release valve, the pressure transducer immediately detects a pressure change in the well and exhibits a rapid drop in pressure (equal to the induced pressure head in the well), which then begins to recover back to the pretest water level in the well. The rate of recovery is proportional to the hydraulic conductivity. The test data is transmitted to a data file on the laptop for later analysis.

For slug-in tests the following procedure was followed. The Whitey ball valve was turned to isolate the pressure side of the system and the Nupro valve on the manifold assembly was closed to isolate the pressure gage. The vacuum assembly was then connected to the vacuum side of the Brailesford pump. Before turning on the pump, all valves on the vacuum setup side were fully opened. The pump was then turned on and the vacuum adjusted by partially closing the Nupro precision valve. The vacuum was monitored with the Magnehelic gage. The pressure transducer was then monitored until it returned to the starting pressure reading. The inlet valve was then closed isolating the wellhead from the pump. The Magnehelic gage was monitored to ensure that vacuum pressure was stable and there was no leakage. To initiate the test,the release valve was opened. Upon opening the release valve the pressure transducer immediately detects a pressure change in the well and exhibits a rapid increase in pressure (equal to the induced vacuum head in the well), which then begins to recover back to the pretest water level in the well. The test data is transmitted to a data file on the laptop for later analysis.

The slug-in and slug-out tests were repeated in triplicate over a short time frame of only a few minutes. At this test site recovery occurred over just a few seconds.

3.4.2 Slug Test - During Development

Following pre development tests, the wells were developed (Table 3-1, Column 4,5,6). The development procedure entailed lowering the surge block with the top valve open to the bottom of the well. Upon reaching the bottom of the well, the valve was closed and the surge block was pulled upward across the well screen. This action created a vacuum in the well, which draws sediment-laden water into the well bore. The valve was then opened and the surge block was again lowered to the bottom of the well. This process was repeated approximately 50 times. The well was then pumped out and the turbidity monitored. With pumping the turbidity typically started at over the meter range (999 NTUs), but then dropped to a value <30 NTUs. Once the water clarified the wells were then slug tested again using the same procedure as above (See Table 3-1, Tests 4, 5, and 6). Development was repeated and then the wells retested. If the hydraulic conductivities were similar to the previous values, development was discontinued. If not, development was repeated until the hydraulic conductivity values appeared to no longer significantly change. With one exception the hydraulic conductivity values stabilized after two development rounds.

3.4.3 Slug Test - Post Development

In order to determine if there were systematic differences in hydraulic conductivity values derived from slug tests before and following development, post development slug tests were run (Table 3-1, Column 7,8,9). After two rounds of rigorous

development followed by slug tests that yielded stable conductivity values post development triplicate slug tests were conducted.

Slug tests were performed at two higher (and/or lower) heads in each well to determine if the duration (and associated zone of influence) and initial head influenced the hydraulic conductivity value (Table 3-1, Column 10,11). Initial heads used in these tests ranged from 0.66 to 4.39 feet. The goal was to perform three 1 ft head displacements followed by three or more of varying head changes. If there was no risk of the water table intersecting the screened interval, both slug in and out tests were conducted.

3.4.4 Pumping Tests

Constant head steady state pumping tests were conducted in each well that was slug tested. The results from these tests provided a means to evaluate the validity of the short duration pneumatic slug tests. The pumping tests were conducted to further evaluate zone of influence bias, and to determine if there was a possible bias because of the presence of so many wells in a single location that may act as storage reservoirs. The unsteady state portions of the pumping tests were also analyzed for hydraulic conductivity. In these tests only the pumping well data were used. Because the transient state only lasted a few seconds, it was not possible to accurately correlate the test time between the pressure transducer in the pumping well and the transducer in the monitoring well.

For the one well steady state test and the unsteady state test, the Geoprobe® pressure transducer was lowered into a well to a known depth. Pumping commenced at the highest rate obtainable without dewatering the well and continued until a steady state

head was reached as indicated by a stable pressure transducer reading. The pumping rate was then incrementally lowered to at least three (or more if attainable) different flow rates until steady state drawdowns were achieved at each flow rate. These tests were performed using pumping rates between 72 ml/min to 4.9 L/min depending on what the well could yield.

Figure 3-13. Pump Test Setup

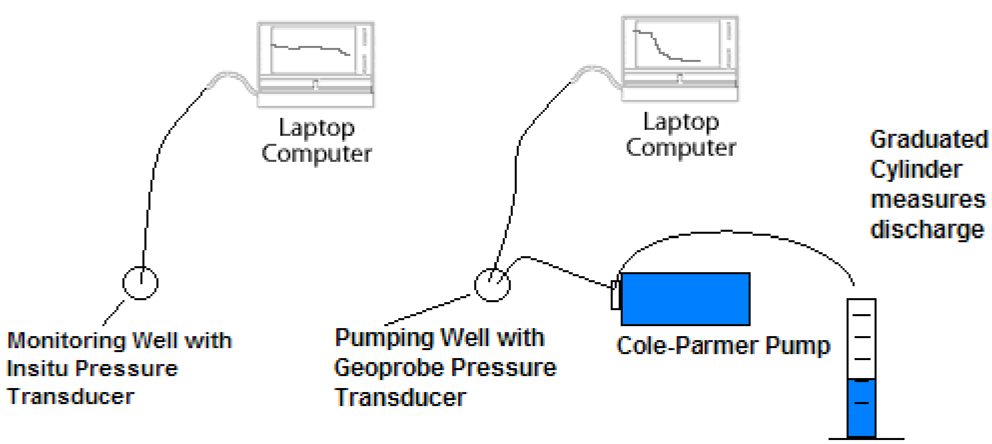


Figure 3-14. Drawing of Pump Test Configuration

Two well steady state tests entailed the same setup at the same time as the one well tests. However, a second pressure transducer was placed at a known distance away from the pumping well (Figure 3-13 and 3-14). The two pressure transducers were then monitored with time.

3.4.5 Test for Spatial Heterogeneity

In order to evaluate the degree of spatial heterogeneity, slug tests, steady state, and unsteady state tests were run in all P1 wells in Cell B (Table 3-1, tests in all P1 wells). Ideally, such an assessment should involve wells with the same screen length and depth. Unfortunately at the test site, the wells in the different clusters were screened over different depth intervals.

3.5 Hydraulic Test Analysis

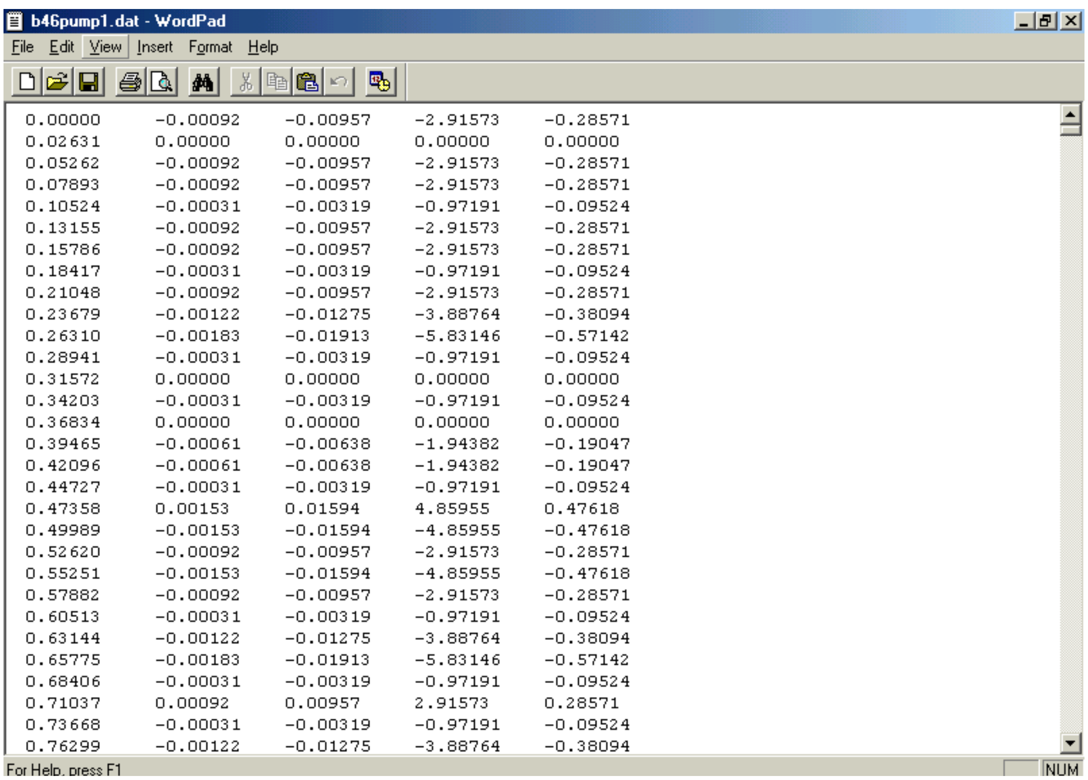
Data analysis entailed calculating hydraulic conductivity values from all tests using several models that fit the well geometries, formation conditions, and well construction specifications. For all the slug tests except well B4-6, which exhibited an oscillatory response, the ellipsoidal intake model compiled in Hvorslev (1951) was used to analyze the data. For B4-6, a revised model by Butler and Garnett (2000) for high oscillatory responses was used. The data from the steady state tests were analyzed using the constant flow model equivalent of that used for the slug tests (Hvorslev 1951). For the unsteady state tests, they were modeled as fully penetrating wells.

Sensitivity analyses were conducted to evaluate how the calculated conductivity values vary owing to differences between model conditions and actual well construction specifications. For example, the model requires an intake length. The construction logs for HSA wells reveal that they have a screened casing section of 2 or 5 ft (0.61 to 1.5 m),

but the gravel pack is 4 to 7 ft (1.2 to 2.1 m) in length. The model also requires a well diameter. The “D” wells have a diameter of 2 in. OD, but were placed in holes that were 8 in. in diameter. To analyze this situation one could use any of the four combinations of intake length and intake diameter (Bouwer and Rice, 1976).

3.5.1 Slug In/Out Hydraulic Conductivity Analysis

In total 296 slug tests were individually analyzed (often multiple times depending on the linearity of the log head vs time curve). After the slug test was run, the Geoprobe® software for the pneumatic system automatically generated an ASCII data file (*.dat). This file contained the raw data on time (s), transducer voltage (v), head (ft), head (mm), and pressure (millibar) (Figure 3-15).



0.00000	-0.00092	-0.00957	-2.91573	-0.28571
0.02631	0.00000	0.00000	0.00000	0.00000
0.05262	-0.00092	-0.00957	-2.91573	-0.28571
0.07893	-0.00092	-0.00957	-2.91573	-0.28571
0.10524	-0.00031	-0.00319	-0.97191	-0.09524
0.13155	-0.00092	-0.00957	-2.91573	-0.28571
0.15786	-0.00092	-0.00957	-2.91573	-0.28571
0.18417	-0.00031	-0.00319	-0.97191	-0.09524
0.21048	-0.00092	-0.00957	-2.91573	-0.28571
0.23679	-0.00122	-0.01275	-3.88764	-0.38094
0.26310	-0.00183	-0.01913	-5.83146	-0.57142
0.28941	-0.00031	-0.00319	-0.97191	-0.09524
0.31572	0.00000	0.00000	0.00000	0.00000
0.34203	-0.00031	-0.00319	-0.97191	-0.09524
0.36834	0.00000	0.00000	0.00000	0.00000
0.39465	-0.00061	-0.00638	-1.94382	-0.19047
0.42096	-0.00061	-0.00638	-1.94382	-0.19047
0.44727	-0.00031	-0.00319	-0.97191	-0.09524
0.47358	0.00153	0.01594	4.85955	0.47618
0.49989	-0.00153	-0.01594	-4.85955	-0.47618
0.52620	-0.00092	-0.00957	-2.91573	-0.28571
0.55251	-0.00153	-0.01594	-4.85955	-0.47618
0.57882	-0.00092	-0.00957	-2.91573	-0.28571
0.60513	-0.00031	-0.00319	-0.97191	-0.09524
0.63144	-0.00122	-0.01275	-3.88764	-0.38094
0.65775	-0.00183	-0.01913	-5.83146	-0.57142
0.68406	-0.00031	-0.00319	-0.97191	-0.09524
0.71037	0.00092	0.00957	2.91573	0.28571
0.73668	-0.00031	-0.00319	-0.97191	-0.09524
0.76299	-0.00122	-0.01275	-3.88764	-0.38094

Figure 3-15. Geoprobe ASCII Data File

A Microsoft® Excel workbook was constructed to facilitate the ease of raw data transfer and analysis. The workbook consists of four worksheets: Raw Data, Raw Data Plot, Raw Log Head vs. Time, and Analysis. The workbooks are contained on the enclosed CD. The procedure for analyzing the data was as follows. A well construction and test description header were filled in with the appropriate information on the Raw Data worksheet. To transfer the data the dat file was opened in a blank Microsoft Excel worksheet and cut and pasted into the Raw Data worksheet. The Raw Data worksheet automatically calculates absolute head and log (head). Both slug-in and slug-out tests were analyzed in the same manner because the absolute value of head is taken.

The second worksheet generates a raw data plot of pressure transducer reading (ft) vs. time (Figure 3-16). This plot was used to locate the recovery portion of the curve.

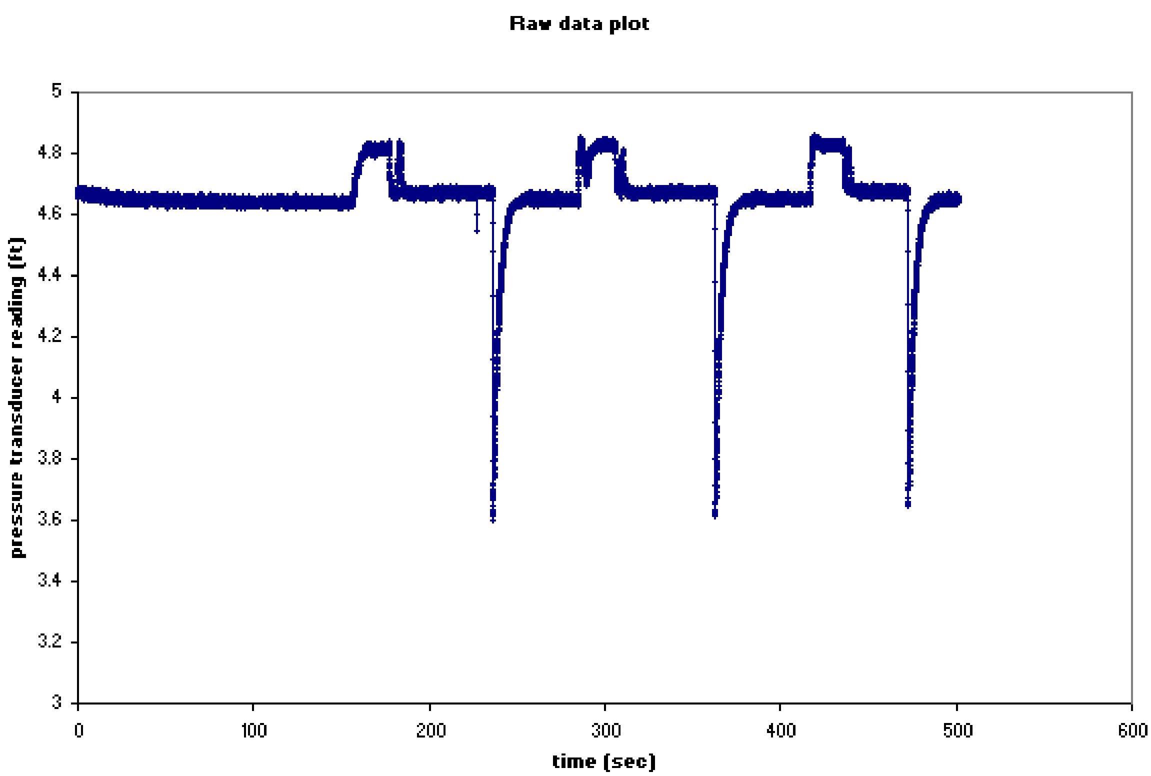


Figure 3-16. Pressure Transducer Reading (ft)

With the recovery portion of the curve located, the raw time versus log (head) data from the recovery portion of the curve (maximum head induced until recovery) were plotted on the Raw Log Head vs. Time worksheet (Figure 3-17). Typically the raw time versus log(head) curve was log linear in early time and became non-log linear in later time. It should be noted that the apparent scatter in the late time data represents only a small variation in head (< 0.02 feet).

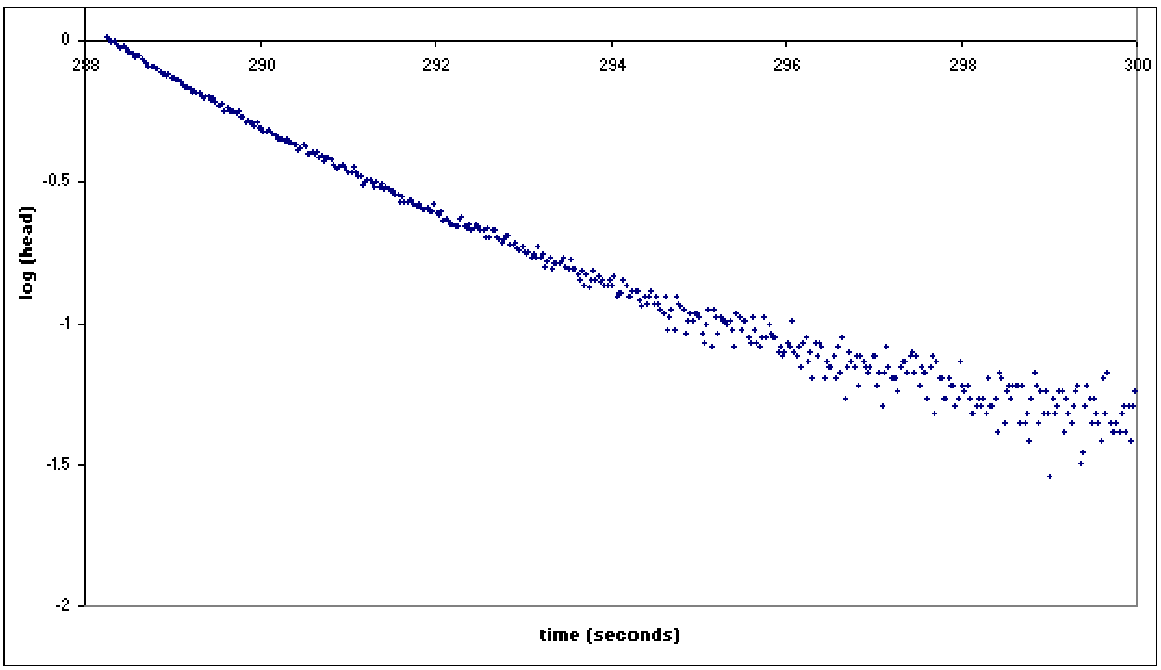


Figure 3-17. Time vs. Log (Head) Output

Based on inspection, the log linear portion the Raw Log Head vs. Time was transferred to the Analysis worksheet (Figure 3-18).

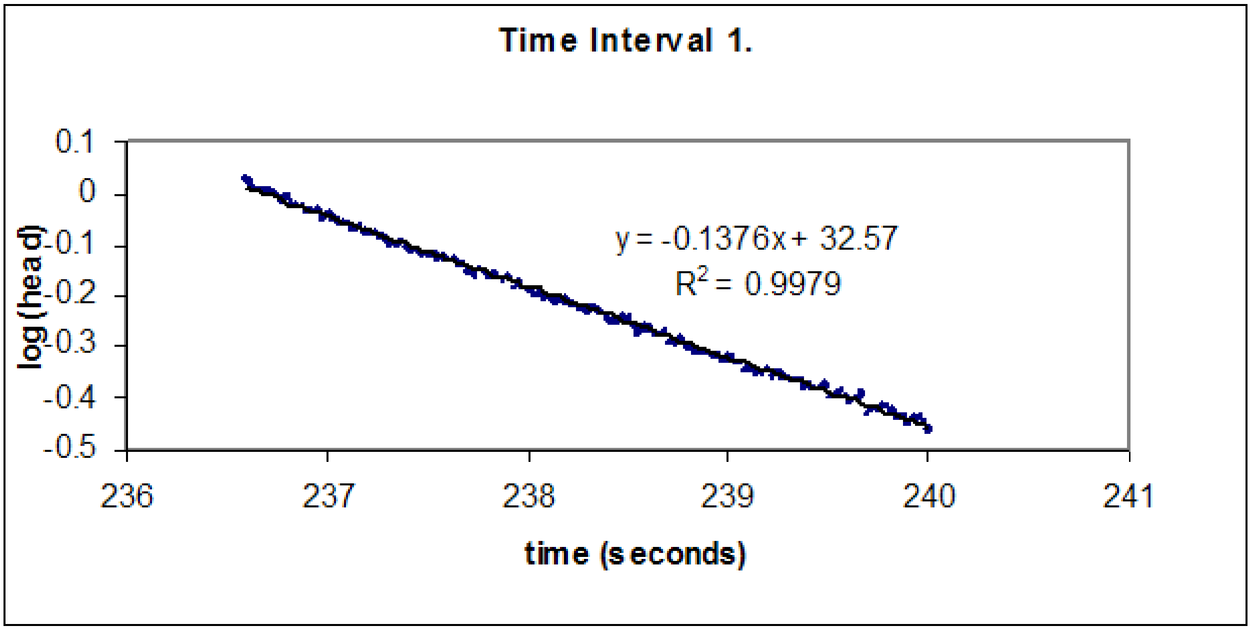


Figure 3-18. Log Linear Portion of Graph Analyzed

Though a majority of the well response curves exhibited the characteristic log linear recovery some wells had non-characteristic recoveries, which will be discussed in section 5.1.9. The Analysis worksheet then calculates hydraulic conductivity (Figure 3-19). A

Corrected Casing Diameter (ft):	0.1656	
Saturated Intake Length (ft):	4.50	
Intake Diameter (ft):	0.67	
Length of Analysis:	3.42031	sec
Length until Recovery:	21.20586	sec
% curve Analyzed:	16%	
% curve of total head:	67%	

Regression Method

$$k = \frac{(-\text{slope})\, D_r^2\, 5.304 \log \left[L/D + [1 + (L/D)^2]^{1/2}\right]}{8L}$$

Slope =	-0.13761409	
k=	54.42	ft/day
k=	1.92E-02	cm/s

Figure 3-19. Data Analysis Output

workbook may contain more than one Analysis worksheet depending on the number of contained in the original data file.

In all wells, except B4-6 (the oscillatory response well), the ellipsoidal intake model compiled in Hvorslev (1951) in a regression format was used:

$$K = \frac{(-slope)\cdot {D_r}^2 \cdot 5.304 \cdot \log \sqrt{\left[\frac{L}{D}\right] + \left[1 + \left(\frac{L}{D}\right)^2\right]}}{8L} \qquad (3\text{-}2)$$

Where:

K = hydraulic conductivity (ft/day)
Slope = slope of. log (head) vs time curve
D_r = corrected casing diameter (ft) = $(D_c^2 - P_d^2)^{1/2}$
D_c = inner casing diameter (ft)
P_d = outer diameter of the pressure transducer cable (in this case equal to 0.01875 ft)
L = saturated intake length (ft)
D = intake diameter (ft)

In the oscillatory well, a revised model by Butler and Garnett (2000) for slug tests in high permeability formations was used to determine the hydraulic conductivity value. Their model in the form of an Excel workbook is available in an open-file report at www.kgs.ukans.edu. The analysis entailed the following methodology:

1. In a blank Excel worksheet pressure transducer reading versus time was plotted for the entirety of the test. From this plot, the test starting point was identified. The head vs. time data set for the recovery portion of the curve were input into “Sheet 2” under “Time in Seconds” and “Pressure Head in Feet ” columns. Input The general test data, well construction parameters, and the static

water level were also entered into "Sheet 2" (Figure 3-20).

High K Estimator Spreadsheet English Units			Test Well Specs - "d" not used in confined case		
			Depth to Bottom of Screen (from toc):	17.6	ft
			Screen Length (b):	5	ft
General Test Data			Depth to Static Water Level (from toc):	5.42	ft
Site Location:	Port Hueneme, CA		Top of Screen to Water Table (d):	7.18	ft
Date:	3/12/2003		Radius of Well Screen (r_w):	0.058	ft
Time:			Nominal Radius of Well Casing (r_{nc}):	0.031	ft
Test Designation:	B46 High K dd 5		Radius of Transducer Cable (r_{tc}):	0.009	ft
Static Level:	7.00	ft	Effective Casing Radius (r_c = (r_{nc}^2-r_{tc}^2)^0.5):	0.030	ft
Initial Water Level			Modified Screen Radius (r_w*):	0.058	ft
Change (H_0):	-2.39	ft	Aspect Ratio (b/r_w*):	85.714	
Start Time for Test	164.62167	sec	Formation Thickness (B):	12.6	ft

Time in seconds	Pressure Head in feet	Test Time	Deviation From Static	Test Time	Normalized Head
164.62167	4.51199	0	-2.487	0	1.039
164.64798	4.55982	0.02631	-2.439	0.02631	1.019
164.67429	4.57257	0.05262	-2.427	0.05262	1.013

Figure 3-20. High Hydraulic Conductivity Estimator Spreadsheet (Butler and Garnett, 2000)

2. Static pressure head and the test start time were subtracted from the head and time data and subsequently plotted (difference of the pressure head from static versus the time since the test commenced) on "Chart 2" (Figure 3-21). A data test set, which includes "Test Time" and "Normalized Head" were automatically generated and plotted on "Chart 3" (Figure 3-22).

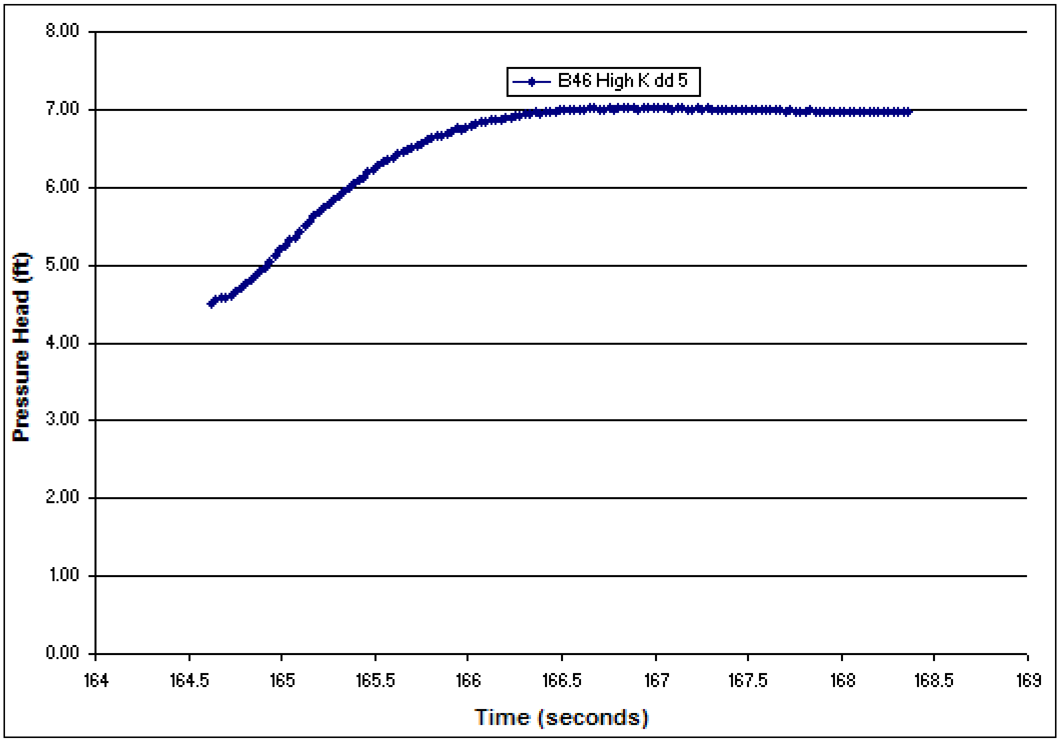


Figure 3-21. Chart 2, Pressure Head (ft) vs. Time (s)

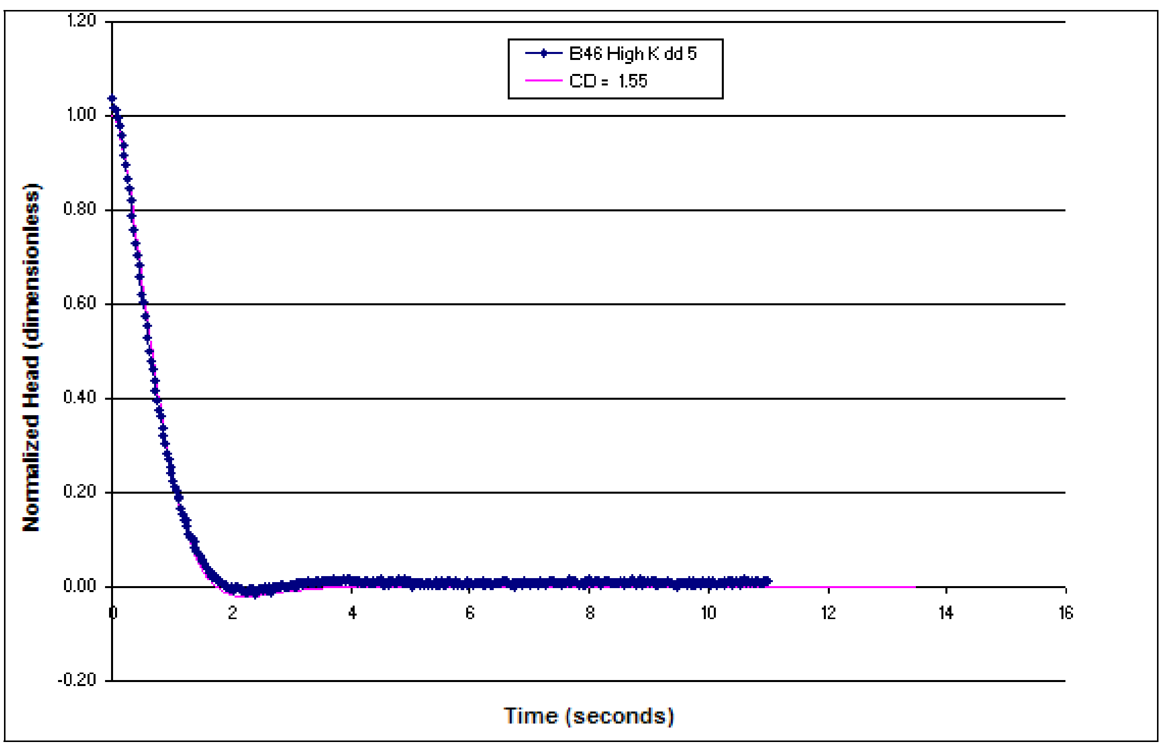


Figure 3-22. Chart 3, Curve Matching

3. For a given value of the dimensionless dampening parameter (C_D , see below) the spreadsheet generated a theoretical data set of dimensionless time and normalized head in “Sheet 1.” Using this data a theoretical type curve was automatically generated in “Chart 1” (Figure 3-23, 3-24). The type curve based on the oscillatory equations developed by Zlotnik and McGuire (1998). These are:

$$w_d\left(t_d\right) = e^{-\left(\frac{C_d}{2}\right)\cdot t_d} \cdot \left[\cos\left(\omega_d \cdot t_d\right) + \left(\frac{C_D}{\left(2\omega_d t_d\right)}\right) \cdot \sin\left(\omega_d t_d\right)\right], C_d < 2 \qquad (3\text{-}3)$$

$$w_d\left(t_d\right) = e^{-\left(t_d\right)}\left(1 + t_d\right), C_d = 2 \qquad (3\text{-}4)$$

$$w_d\left(t_d\right) = \left(\frac{1}{\left(w_d^{\ +} - w_d^{\ -}\right)}\right) \cdot \left(w_d^{\ -} \cdot e^{w_{d+} \cdot t_d} - w_d^{\ -} \cdot e^{w_d - t_d}\right), C_D > 2 \qquad (3\text{-}5)$$

Where:

C_D = dimensionless dampening parameter (constant of proportionality that influences both the amplitude and frequency of the theoretical oscillation)
g = gravitational acceleration
H_o = initial displacement
t_d = dimensionless time parameter; $(g/L_e)^{1/2}\ t$
t = time
w = head
w_d = normalized head (w_o/H_o)
$\omega_d^{+/-}$ = dimensionless frequency parameter; $- C_D/2 +/- \omega_d$
g = gravitational acceleration
L_e = length of the water column above the screen

Type Curve Generator Spreadsheet

C_D	omega	omega+	omega-
1.55	0.6320	-0.1430	-1.4070

Orange	Designates parameter to be adjusted in curve matching
Yellow	Designates user-entered test or well data
Green	Designates calculated hydraulic conductivity estimate

Dimensionless Time	C_D = 1.55
0	1.0000
0.1	0.9953
0.2	0.9820
0.3	0.9615
0.4	0.9351
0.5	0.9038
0.6	0.8687
0.7	0.8305
0.8	0.7901
0.9	0.7483
1	0.7055

Figure 3-23. Sheet 1, Type Curve Generator Spreadsheet

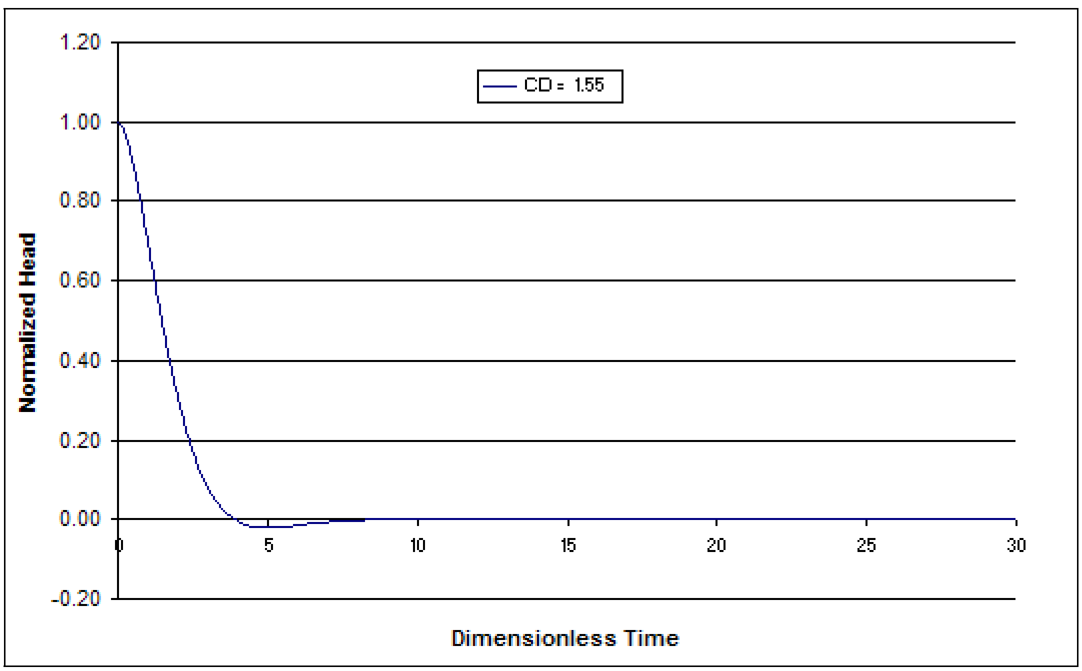


Figure 3-24. Chart 1, C_D Type Curve

4. The test data were then matched to the type curve in “Chart 1” on “Chart 3” (Figure 3-22) by changing the value of C_D. This was accomplished by adjusting

the C_D on “Sheet 1”and a “Modulation Factor” on “Sheet 2.” The modulation factor stretches or shrinks the theoretical type curve along the dimensionless time axis.

5. Once the C_D value and modulation factor were obtained they were substituted into a modified version of the Hvorslev equation 2-1 (Figure 3-25) to solve for the hydraulic conductivity.

Confined - High-K Hvorslev Model				
K_r =	t_d* r_c^2 ln[b/(2r_w*)+(1+(b/(2r_w*))^2)^0.5]			
	t*	2bC_D		
Bracketted quantity				85.726
K_r =	5.67E-04 ft/sec			
	4.90E+01 ft/day		1.49E+01 m/day	
	1.73E-02 cm/sec			

Figure 3-25. Sheet 2, Hydraulic Conductivity Calculator

3.5.2 Steady State One & Two Well Hydraulic Conductivity Analysis

One well steady state hydraulic conductivity tests were analyzed using a spreadsheet developed by Robbins (2000) (Figure 3-26).

Single Well Steady State Pumping Test

Sampler Info		Site Info	
Static P transducer reading(ft)	3.51074	Site	Port Hueneme, CA
Casing Diameter (ft):	0.0625	Sampler No.	B16
Saturated Screen Length (ft):	2	Date	03/17/03
Screen Diameter (ft):	0.12	Personnel	S. Bartlett / G. Robbins
Geometry:	full ellipse		

Measurements for Constant Drawdown

test	Steady State P transducer reading (ft)	Flow Rate Q(ml/min)	Steady State head (ft)	Flow Rate, Q (ml/sec)
test a	2.2	3495	1.31074	58.25
test b	2.47	2830	1.04074	47.17
test c	2.8	1750	0.71074	29.17
test d	3.06	960	0.45074	16.00
test e	3.23	625	0.28074	10.42
test f	3.28	410	0.23074	6.83
test g	3.33	240	0.18074	4.00

slope (Q/h)=	48.23824	ml/sec/ft	Constant Head Equation
k=	4.14E+01	ft/day	k= slope 2.303 log [L/D + (1+(L/D)[illegible])[illegible]]
k=	1.46E-02	cm/s	2πL

Comments:

Figure 3-26. Single Well Steady State Pumping Test Analysis Sheet

The general test description, steady state flow rates, and drawdowns were input into the spreadsheet. The spreadsheet calculated the steady state heads and developed a plot of discharge versus steady state head (Figure 3-27). The spreadsheet then generated a slope for the curve. The hydraulic conductivity was determined from the slope of the curve using the steady state flow equation (3-6) for an ellipsoidal source (Hvorslev, 1951).

$$K = \left[(-\,slope) \cdot 2.303 \cdot \log \sqrt{\left[\frac{L}{D}\right] + \left[1 + \left(\frac{L}{D}\right)^2\right]} \right] / \, 2\pi L \qquad \text{(3-6)}$$

K = hydraulic conductivity
L = saturated screen length
D = screen diameter

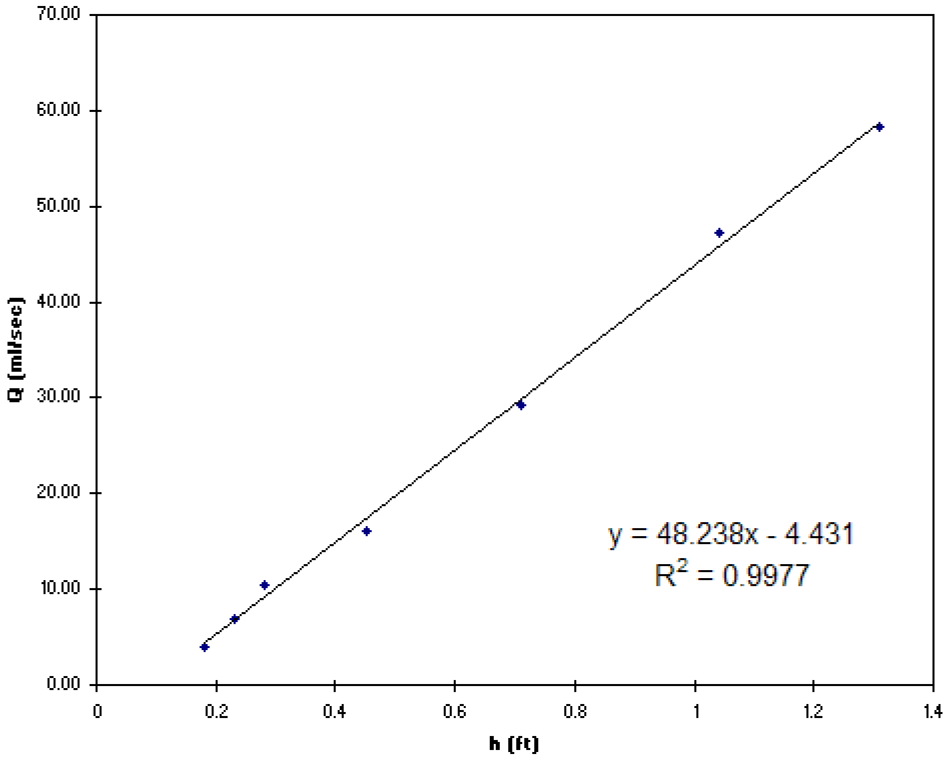


Figure 3-27. Discharge vs. Head from Steady State Pump Test Data

Two well steady state hydraulic conductivity analyses utilized steady state heads from the pressure transducers located in the pumping and observation wells. During data collection, the pressure transducer readings were monitored as a function of time to determine when steady state heads are reached at the different discharge rates. With the time axis of both plots normalized to a common start time the steady state heads in both wells were determined for each discharge rate. The radial distance between the wells along with the screen length, which was taken as the aquifer thickness, and the steady state drawdowns for a given discharge were substituted into the equation 2-7 to solve for the hydraulic conductivity (Thiem, 1906). The calculation was performed using an Excel spreadsheet (Figure 3-28).

$$K = \left(\frac{Q}{2\pi b} \cdot (s_1 - s_s) \right) \cdot \ln\left(\frac{r_1}{r_2} \right) \qquad (3\text{-}7)$$

Where:

Q = pumping discharge
b = saturated screen length
s_1 = drawdown at r_1 from the pumping well
s_2 = drawdown at r_2 from the pumping well
r_1 = radius of pumping well
r_2 = radius from the pumping well

Two Well Steady State Test Pumping Test using the Thiem Equation			
Equation: $K = (Q / 2\pi b\ (s_1 - s_2\ ))*\ln(r_1/r_2)$			
Pumping Well	**B16**		
Observation Well	**B15**		
Q (pumping discharge) =	2830	ml/min =	47.2 ml/sec
b (saturated screen length) =	2	ft =	61.0 cm
s_1 is drawdown at r_1 from the pumping well =	-1.04	ft =	-31.7 cm
s_2 is drawdown at r_2 from the pumping well =	-0.115	ft =	-3.5 cm
r_1 radius of pumping well =	0.058333	ft =	1.8 cm
r_2 is radius from the pumping well =	3.416	ft =	104.1 cm
K =	1.78E-02 cm/sec		

Figure 3-28. Two Well Steady State Thiem Analysis Sheet

3.5.3 One Well Unsteady State Hydraulic Conductivity Analysis

To conduct analysis of the one well unsteady state data HydroSOLVE, Inc. AQTESOLV® for Windows® Version 3.01.was used (Figure 3-29). The portion of the drawdown curve from the start of pumping until just prior to steady state was analyzed. The software requires the input of the saturated thickness (assumed to be the screened interval, “b”), initial pumping rate, well construction, and pumping well drawdown with time. AQTESOLV® generates a transmissivity value “T” which can then be used to calculate hydraulic conductivity knowing the aquifer thickness (Figure 3-28).

$$K = \frac{T}{b} \tag{3-8}$$

Where:

K = hydraulic conductivity
T = transmissivity
b = aquifer thickness

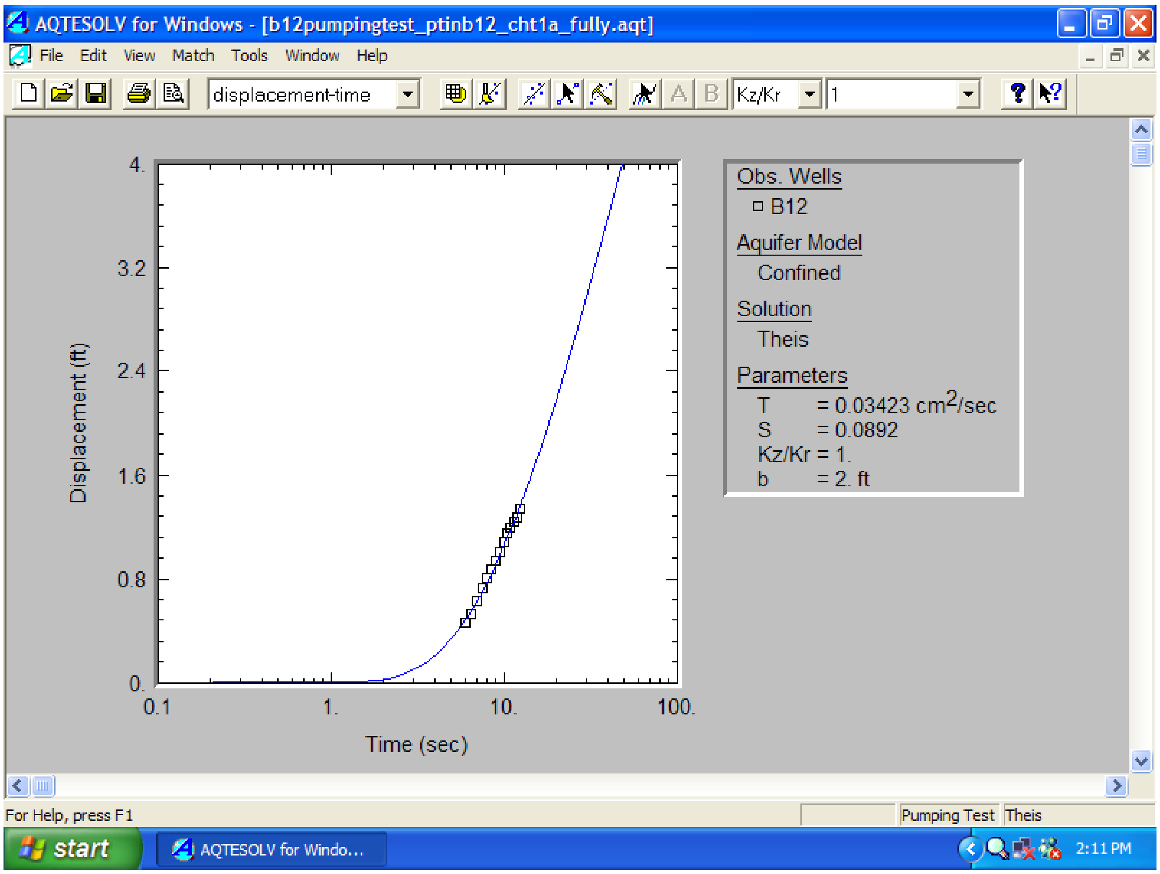


Figure 3-29. AQTESOLV® Analysis

The software has several different built in models to analyze the pumping data. Based on a sensitivity analysis, the differences between hydraulic conductivity values computed using different models (the confined Theis model and both partially and fully penetrating scenarios for the unconfined Theis and Neuman models) was negligible. This is perhaps because of the short distance between the pumping and observation wells (only 1.8 to 3.9 ft) and the very short duration of the transient state (a few seconds at most).

3.6 Statistical Analysis Performed

Comparative statistical analyses were performed in conjunction with Dr. Michael Barcelona and J. Douglas Mandrick of Western Michigan State University. The main goal of the statistical analyses was to determine if there was a significant difference between hydraulic conductivity values determined for the direct pushed wells and the hollow stem auger drilled wells. In order to accomplish this a comprehensive statistical evaluation was performed. MINITAB® (Release 13.0 State College, PA) was used to compute the Analysis of variance (ANOVA) for the statistical comparisons.

3.6.1 Analysis of Variance (ANOVA)

Independent data sets were compared to each other in order to determine if they were statistically similar or different. Given the nature of the lengthy data set, ANOVA was the prescribed analysis method. Values of hydraulic conductivity for different tests were input into the software in separate columns depending the desired comparison. The program then ran ANOVA on the data and generated an output, which gave the degrees of freedom (DF (number of independent deviations $x_i - x$ which were used in calculating s), sum of the squares (SS), mean square (MS) (sum of squared terms divided by the number of degrees of freedom, F (F-test), and P (probability) as well as the Ns (number of values in the data set), and means, and standard deviations (s) for the given data set..

For the analysis performed F and P were the variables of concern. The F value obtained from the program tests the statistical significance of the observed differences between the means of two or more data sets. The F test was used as a comparison of standard deviation. It tests whether two standard deviations differ significantly and is a ratio of the two sample variances:

$$F = \frac{s_1^{\ 2}}{s_2^{\ 2}} \qquad (3\text{-}9)$$

If the ratio between standard deviations was close to one, then the null hypothesis (no difference between the hydraulic conductivity values) was accepted (Miller & Miller, 1993).

The P value allowed the significance of the test to be determined. Prior to computer software (like MINITAB®) calculating the P-value was done by comparing a value to a table of threshold values for correlation depending on your sample size. Today statistical programs provide either "the probability corresponding to your observed correlation" or "the probability of something more extreme than your correlation" (Hopkins, 2002). If the P value was < 0.05 then there was a statistical difference between the data sets, but if the P value was > 0.05 then there was not a statistical difference between data sets. It is important to note that P values do not provide one with a yes/no answer, but rather how strong is the case against the null hypothesis. Therefore the lower the P-value the stronger case that there is a difference between data sets (http://www.texasoft.com/pvalue.html). The P-value is the probability of making a Type 1 error or rejecting the null hypothesis when it is true. (MINITAB® help).

To display the results of the ANOVA tests whisker-box plots were generated in MINITAB®. Figure 30 can be used as a key when viewing these plots.

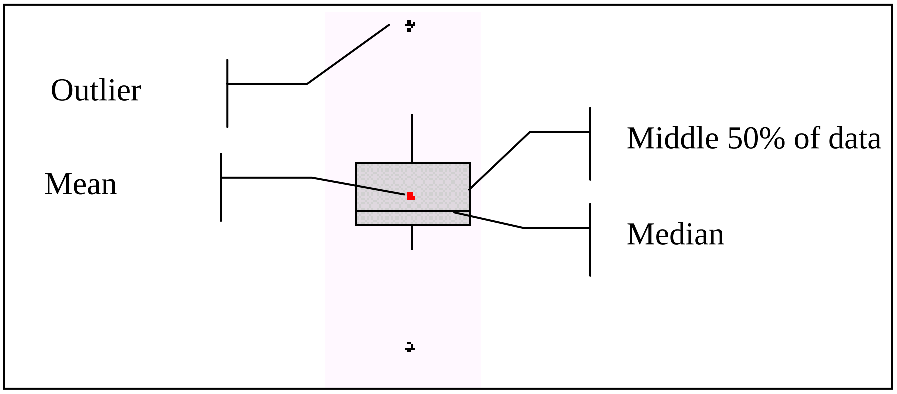


Figure 3-30. Whisker-Box Plot Diagram

4.0 Results

4.1 Tally of Tests Performed

A total of 296 hydraulic conductivity tests were performed over an 13 day period from March 8 to 21, 2003. Table 4-1 summarizes the tests conducted.

Table 4-1. Test Completion Table

Total 296 tests in 13 days
Pneumatic slug tests (245)
- Pneumatic slug-in (vacuum) tests
- Pneumatic slug-out (pressure) tests
Unsteady state pumping tests (19)
Steady state pumping tests
- One well pumping tests (15)
- Two well pumping tests (17)

Figure 4-1 summarizes the average post development hydraulic conductivity values by well and test method. The hydraulic conductivity from these tests ranged from 1.6×10^{-4} to 6.0×10^{-2} cm/s with a mean value of 1.5×10^{-2} cm/s. Post development slug tests had a reproducibility of approximately 18 % RSD (the average standard deviation divided by the mean).

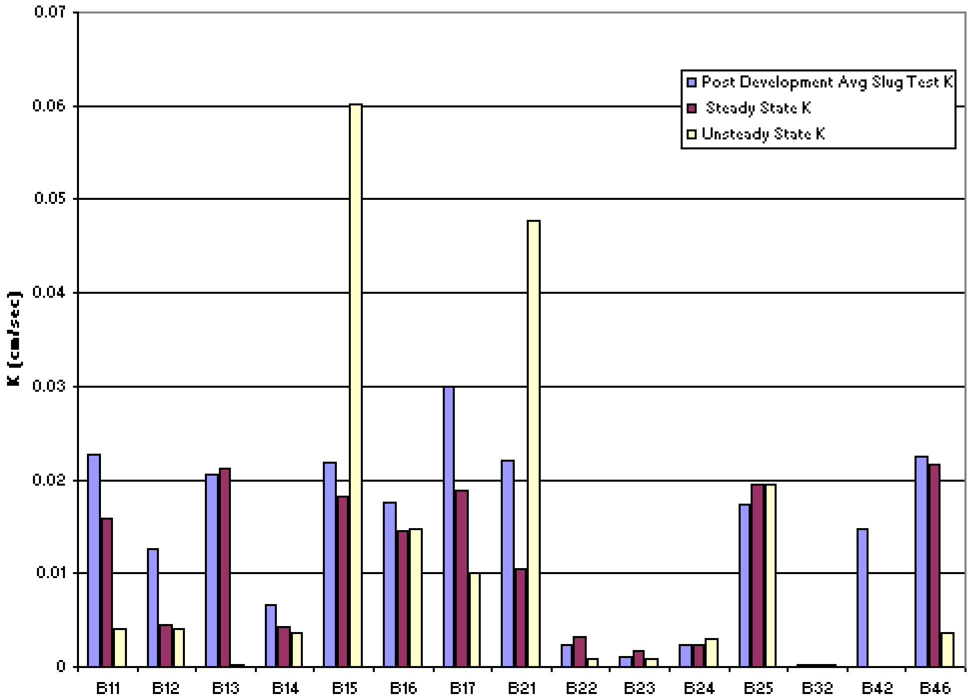


Figure 4-1. Result Comparison by Test Method

The test results were used to examine factors that could influence the determination of hydraulic conductivity amongst the different well types. The results are presented below in a manner that addresses these factors.

4.2 Individual Well Issues

4.2.1 Pre, During, and Post Development Hydraulic Conductivity Comparison

In order to determine if hydraulic conductivity values varied with development, ANOVA was run on the pre development and post development hydraulic conductivity values for all 15 wells. Statistical differences were found between pre and post development hydraulic conductivity values in 10 wells with 5 wells showing no differences. Of the 10 wells that had a statistical difference between pre and post development, 5 wells increased and 5 wells decreased in conductivity with development (Table 4-2). For the wells where hydraulic conductivity increased, the values changed from 1.2 to 2.1 times with development. In the wells whose hydraulic conductivity

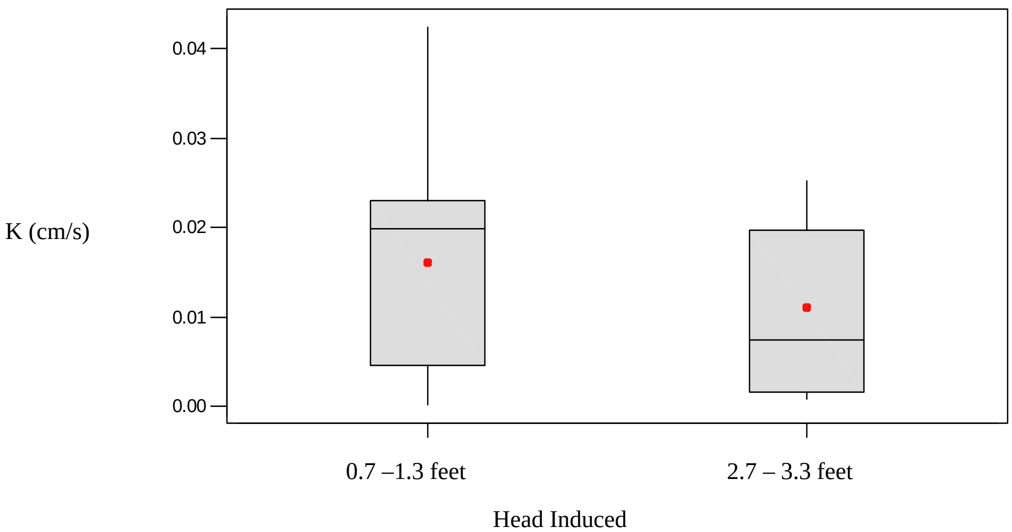
decreased, the values changed from 1.6 to 3.6 times. There did not appear to be any systematic variation in conductivity with development associated with a particular well type.

Table 4-2. Development Impact

Well	F	P	Significant difference?	K up down?	Well Type
B22	2883.33	0.000	Y	down	p1
B16	4.86	0.055	N		p1
B12	15.17	0.004	Y	down	p1
B32	127.41	0.000	Y	down	p1
B42	33.23	0.004	Y	up	p1
B46	21.41	0.000	Y	up	p1
B24	1.33	0.293	N		p
B14	7.90	0.020	Y	up	p
B25	0.04	0.851	N		d
B17	0.47	0.508	N		d
B15	14.30	0.003	Y	up	d
B23	217.10	0.000	Y	down	pcv
B13	0.10	0.765	N		pcv
B21	72.97	0.000	Y	up	pnp
B11	18.59	0.002	Y	down	pnp

4.2.2 Induced Head Change Comparison

To evaluate whether the magnitude of induced head influenced the post development hydraulic conductivity values from slug-in and slug-out tests, an ANOVA was performed comparing induced heads that ranged from 0.7 - 1.3 ft with those that ranged from 2.7 - 3.3 ft for all well types. These values of induced head corresponded to head changes that ranged from 6% to 71% of the water column in the wells. No statistical difference was found (Figure 4-2). Furthermore, there was no apparent change in hydraulic conductivity with change in head observed in any of the individual wells tested.



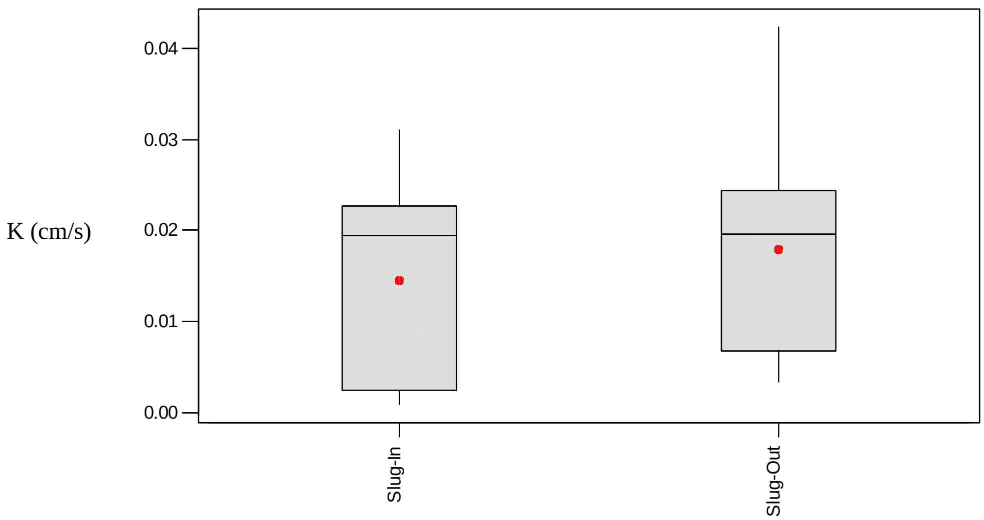
One-way ANOVA: K(0.7-1.3), K(2.7-3.3)

```
Analysis of Variance
Source      DF        SS        MS        F        P      Stat. Diff.?
Factor       1  0.000191  0.000191     1.82    0.183      No
Error       55  0.005781  0.000105
Total       56  0.005973
                                    Individual 95% CIs For Mean
                                    Based on Pooled StDev
Level        N      Mean     StDev  --+---------+---------+---------+----
K(0.7-1.3) 48   0.01605   0.01036                    (-----*-----)
K(2.7-3.3)  9   0.01103   0.00961  (-------------*-------------)
                                    --+---------+---------+---------+----
Pooled StDev =  0.01025             0.0050    0.0100    0.0150    0.0200
```

Figure 4-2. Induced Head Comparison

4.2.3 Slug In/Out Hydraulic Conductivity Value Comparison

Comparative ANOVA tests were run to evaluate whether post development slug-in tests results were statistically different from slug-out tests. Figure 4-3 summarizes the results. Both slug-in and slug-out tests were conducted in three wells in clusters B1 and B2. Slug-in and slug-out tests yielded mean hydraulic conductivity values of 1.5 x 10^{-2} cm/s and 1.8 x 10^{-2} cm/s respectively. No statistically significant difference was observed.



One-way ANOVA: Slug-In (-), Slug-Out (+)

```
Analysis of Variance
Source     DF        SS        MS        F        P     Stat. Diff.?
Factor      1  0.000246  0.000246     2.40    0.125     No
Error      82  0.008401  0.000102
Total      83  0.008647
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --+---------+---------+---------+----
Slug-In    48   0.01450   0.01023   (--------*---------)
Slug-Out   36   0.01795   0.00997             (----------*----------)
                                   --+---------+---------+---------+----
Pooled StDev =  0.01012            0.0120    0.0150    0.0180    0.0210
```

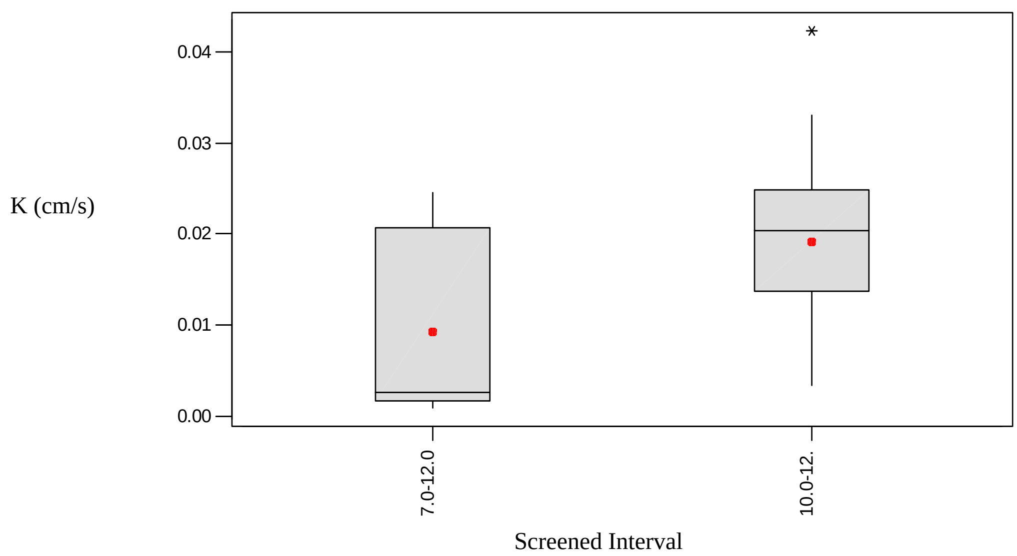
Figure 4-3. Slug in vs. Slug out Comparison

4.3 Issues Relating to Well Depth, Location, and Type

4.3.1 Screen Length Comparison

Wells in the B1 and B2 clusters were statistically compared. Recall the wells in the B1 cluster have two-foot screened intervals and the wells in the B2 cluster have five-foot screened intervals that overlap the two-foot screened intervals. The results are summarized in Figure 4-3. The ANOVA results indicated there was a significant difference in hydraulic conductivity values between these two wells. However, the mean

values of these two data sets differ by only a factor of two and fall well within two standard deviations of one another.



One-way ANOVA: Screen Length 7.0-12.0, 10.0-12.0 Comparison

```
Analysis of Variance
Source     DF        SS        MS        F        P     Stat. Diff.?
Factor      1 0.0017947 0.0017947    21.48    0.000     Yes
Error      82 0.0068510 0.0000835
Total      83 0.0086456
Individual 95% CIs For Mean
Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
7.0-12.0   27  0.009260  0.009501   (------*------)
10.0-12.   57  0.019157  0.008968                     (----*----)
---------+---------+---------+-------
Pooled StDev = 0.009140                   0.0100    0.0150    0.0200
```

Figure 4-4. Screen Length Comparison

4.3.2 Comparison Between P1 Wells

Slug tests were conducted in six P1 wells (3/4”, Pushed ASTM Design Prepack) in all four of the clusters to ascertain the degree to which the hydraulic conductivity values may vary spatially. Unfortunately, the P1 wells were screened over different intervals, which complicated the evaluation of spatial heterogeneity. As shown in Figure

4-5 the conductivity values exhibited an increase then a decrease with the screen midpoint depth. A similar trend was observed in the results from laboratory hydraulic conductivity tests from a nearby boring (Kram, 2001). These results are also plotted on the figure. Both sets of results are consistent with the observed change in stratigraphy with depth, which coarsens from silt to gravel then fines to clay. Because of the pronounced variation in hydraulic conductivity with depth, an ANOVA for the P1 well comparison was judged to be unsuitable.

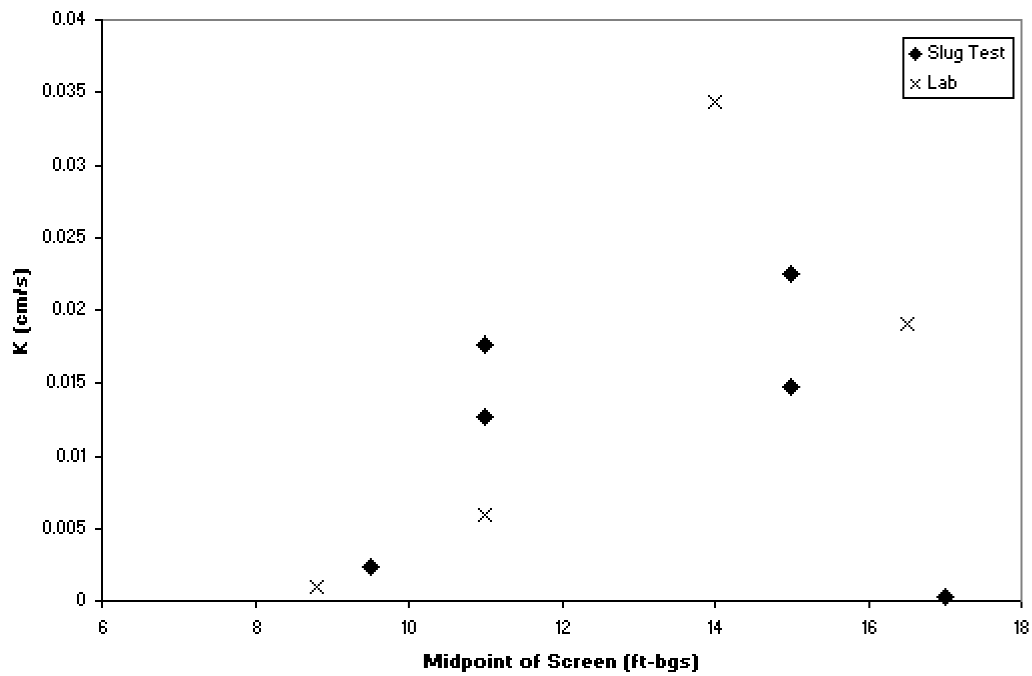
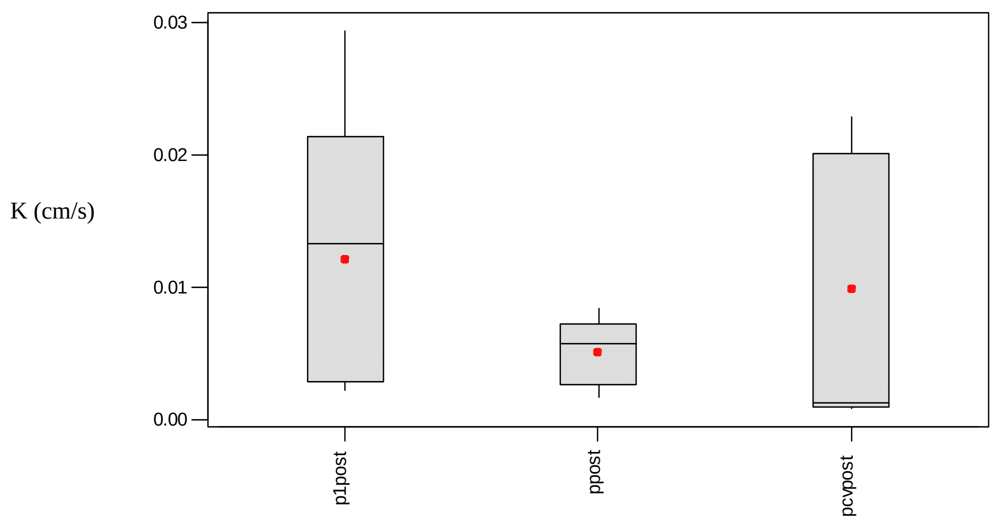


Figure 4-5. Variation of Hydraulic Conductivity with Depth in the P1 Wells

4.3.3 Comparison Between Direct Push Well Types

ANOVA comparisons were made using the post development slug test results between the four direct push well types. The hydraulic conductivity values determined from the three different prepack wells (P1 ¾” ASTM Prepack, P 2” Prepack, PCV ¾” Prepack) were found to not be statistically different (Figure 4-6). The hydraulic

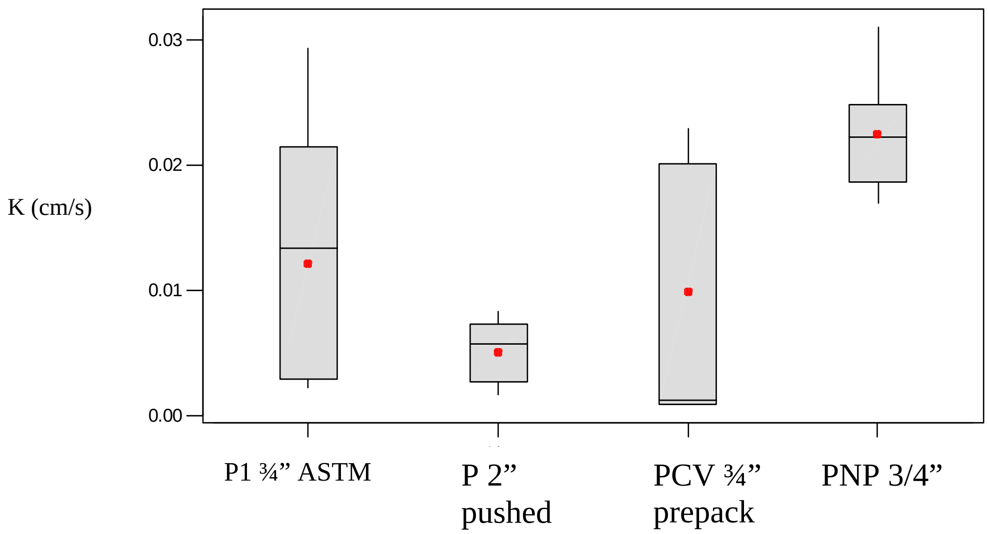
conductivity values for the naturally developed wells were found to be statistically different from the prepack wells (Figure 4-7).



One-way ANOVA: p1post, ppost, pcvpost

```
Analysis of Variance
Source      DF        SS        MS         F        P     Stat. Diff.?
Factor       2 0.0004005 0.0002002      2.77    0.074     No
Error       42 0.0030327 0.0000722
Total       44 0.0034331
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev ----------+---------+---------+------
p1post      21  0.012116  0.009809                  (------*-------)
ppost       13  0.005072  0.002355  (--------*---------)
pcvpost     11  0.009918  0.010207          (----------*---------)
                                   ----------+---------+---------+------
Pooled StDev = 0.008497                    0.0050    0.0100    0.0150
```

Figure 4-6. Prepack Slug Test Hydraulic Conductivity Comparison



One-way ANOVA: P1, P, PCV, PNP Post Comparison

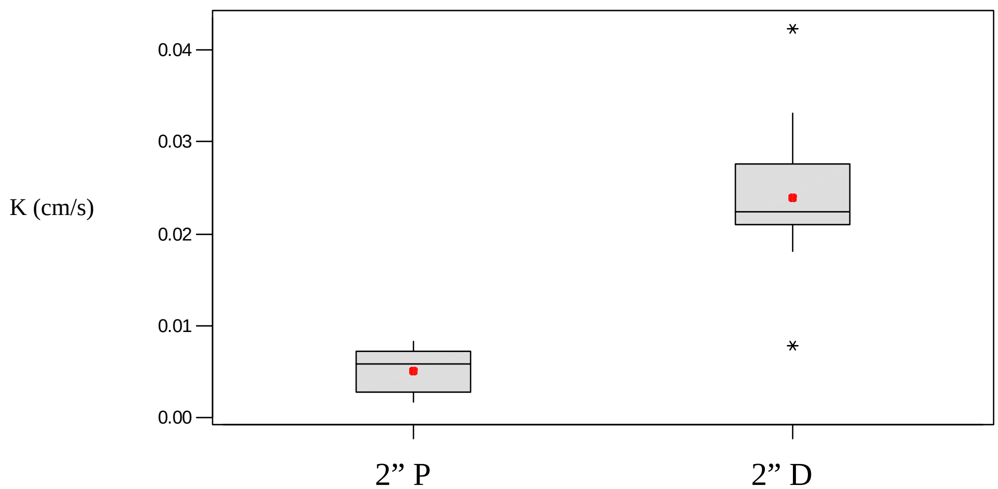
```
Analysis of Variance
Source      DF        SS        MS        F        P      Stat. Diff.?
Factor       3 0.0021800 0.0007267    12.26    0.000      Yes
Error       55 0.0032608 0.0000593
Total       58 0.0054409
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  ---------+---------+---------+-------
p1post      21  0.012116  0.009809            (----*----)
ppost       13  0.005072  0.002355  (-----*-----)
pcvpost     11  0.009918  0.010207         (-----*------)
pnppost     14  0.022453  0.004189                           (-----*-----)
                                   ---------+---------+---------+-------
Pooled StDev = 0.007700                    0.0070    0.0140    0.0210
```

Figure 4-7. Direct Push Well Type Hydraulic Conductivity Comparison

4.3.4 Direct Push Wells vs. Conventional Wells

ANOVA comparisons were performed between the direct pushed wells and the drilled wells using post development slug test data. Figure 4-8 shows the statistical results comparing hydraulic conductivity values for wells having the same diameter (2” diameter prepack (P) and the 2” diameter drilled wells (D)). The 2” diameter drilled wells were found to have hydraulic conductivity values that were statistically different

from the results of the 2" diameter direct push wells.

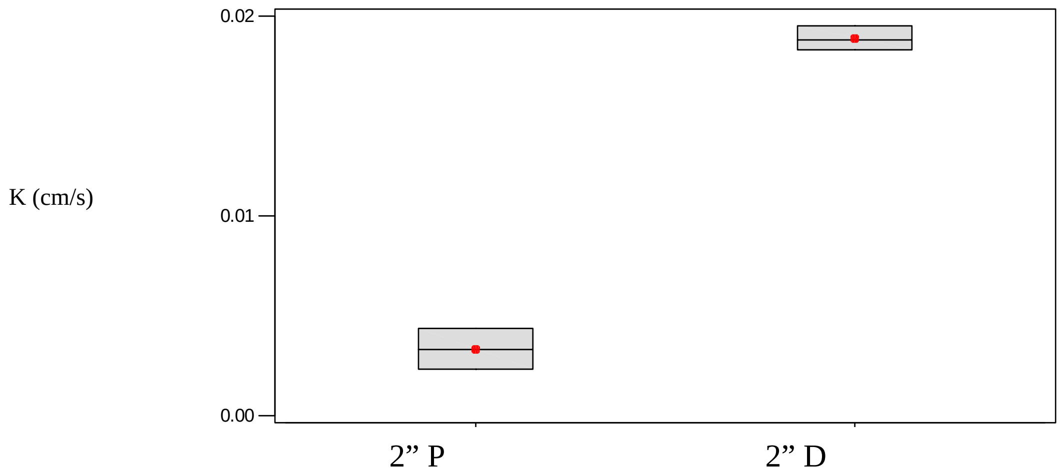


One-way ANOVA: P, D Comparison (Slug Data)

```
Analysis of Variance
Source     DF        SS        MS        F        P     Stat. Diff.?
Factor      1 0.0030406 0.0030406   107.14    0.000     Yes
Error      36 0.0010216 0.0000284
Total      37 0.0040622
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  --------+---------+---------+--------
ppost      13  0.005072  0.002355   (---*----)
dpost      25  0.023927  0.006308                              (--*--)
                                   --------+---------+---------+--------
Pooled StDev = 0.005327                  0.0070    0.0140    0.0210
```

Figure 4-8. Pushed (p) vs. Drilled (d) Wells Hydraulic Conductivity Comparison (Slug Data)

To further evaluate this comparison, ANOVA statistics were computed using the data from steady state tests (Figure 4-9). The results here further confirmed the statistical difference between the hydraulic conductivity values derived from these different well types.

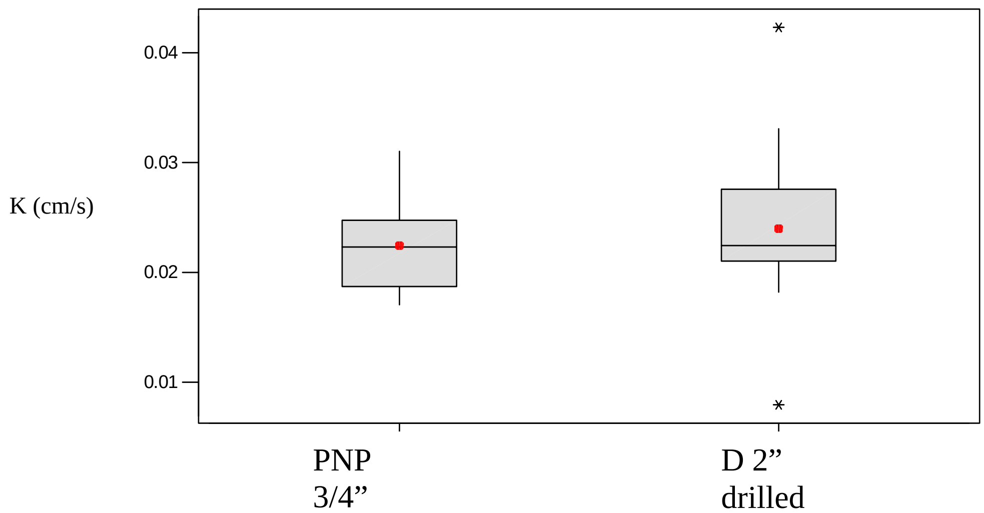


One-way ANOVA: p-SS, d-SS

```
Analysis of Variance
Source     DF        SS        MS        F        P     Stat. Diff.?
Factor      1 0.0002893 0.0002893   301.47    0.000     Yes
Error       3 0.0000029 0.0000010
Total       4 0.0002922
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---------+---------+---------+-------
p-SS        2  0.003340  0.001467   (---*--)
d-SS        3  0.018867  0.000603                              (--*--)
                                   ---------+---------+---------+-------
Pooled StDev = 0.000980                   0.0060    0.0120    0.0180
```

Figure 4-9. Pushed (P) vs. Drilled (D) Wells Hydraulic Conductivity Comparison (Steady State Data)

Figure 4-10 shows the statistical comparison between the naturally developed direct push wells (PNP) and the drilled wells (D). No statistical difference in hydraulic conductivities values was observed. Since the naturally developed well was statistically different from the other direct pushed wells, it follows that the drilled wells are statistically different from all the prepack direct push wells (when the prepacks are grouped together).



One-way ANOVA: PNP, D Post Comparison

```
Analysis of Variance
Source      DF        SS        MS         F        P      Stat. Diff.?
Factor       1 0.0000195 0.0000195      0.61    0.440      No
Error       37 0.0011833 0.0000320
Total       38 0.0012028
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev ----+---------+---------+---------+--
pnppost     14  0.022453  0.004189  (--------------*---------------)
dpost       25  0.023927  0.006308             (-----------*----------)
                                   ----+---------+---------+---------+--
Pooled StDev = 0.005655              0.0200    0.0220    0.0240    0.026
```

Figure 4-10. Drilled (D) vs. Pushed No Pack (PNP) Wells Hydraulic Conductivity Comparison

Figure 4-11 provides a summary comparison of all five wells types. Despite computed statistical differences one can observe that overall the hydraulic conductivity values are over a relatively narrow range. The hydraulic conductivity values determined from the different well types in the B1 and B2 clusters had a mean post development value of 2×10^{-2} cm/s and a standard deviation of 8×10^{-3}.

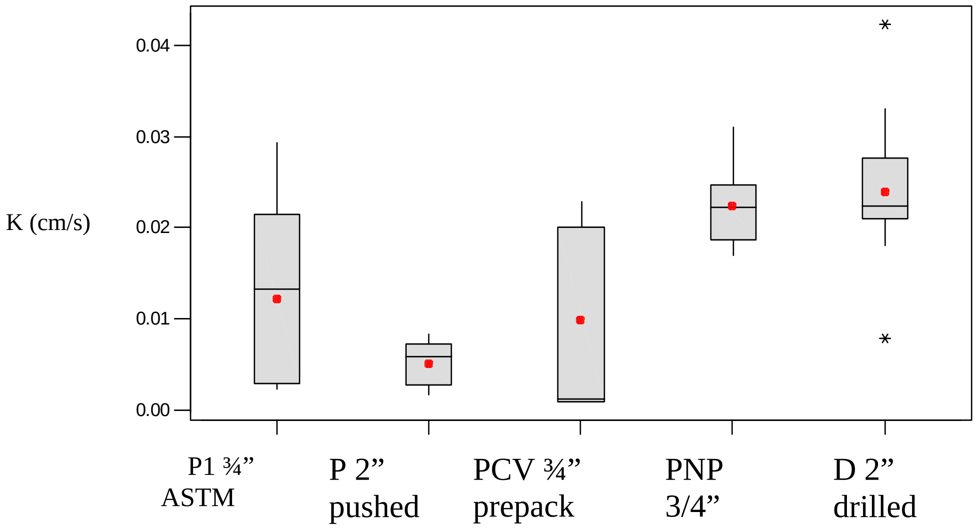
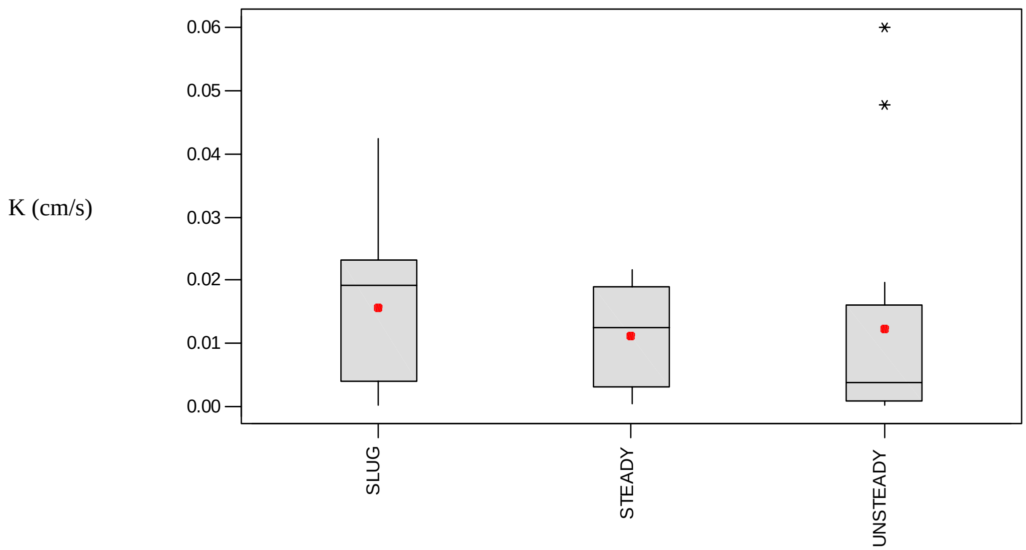


Figure 4-11. Slug Test Well Type Hydraulic Conductivity Comparison

4.4 Issues Relating to Test Method

A critical issue examined here is whether short duration slug tests provide reliable determinations of hydraulic conductivity. To evaluate this issue ANOVA comparisons were performed between post development hydraulic conductivity values determined from one well steady state pumping tests, unsteady state pumping tests, and slug tests. The results are shown in Figure 4-12 and indicate there was no statistical difference in hydraulic conductivity values detected when the test results were grouped strictly by test type.



One-way ANOVA: SLUG, ONE WELL STEADY, UNSTEADY Comparison

```
Analysis of Variance
Source      DF        SS         MS          F         P      Stat. Diff.?
Factor       2  0.000340   0.000170       1.37     0.259      No
Error      134  0.016674   0.000124
Total      136  0.017014
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean      StDev  -----+---------+---------+---------+-
SLUG       109   0.01562   0.01022                          (-----*-----)
STEADY      14   0.01120   0.00816  (----------------*----------------)
UNSTEADY    14   0.01233   0.01866     (----------------*----------------)
                                   -----+---------+---------+---------+-
Pooled StDev =   0.01115               0.0070    0.0105    0.0140    0.0175
```

Figure 4-12. Slug, Steady State, Unsteady State Hydraulic Conductivity Comparison

However, when the comparisons were made based on grouping well type and test type some statistical differences emerged. Table 4-3 and Figure 4-13 compare the steady state and slug test results for the different well types. Based on the ANOVA tests the hydraulic conductivity values determined from the prepack and drilled wells were independent of test type. However, the hydraulic conductivity values determined from slug tests were found to be significantly different from those determined in the one well

steady state pumping tests for the naturally developed direct push wells. For these wells the hydraulic conductivity values from the one well steady state pumping tests were on average about half that of the slug tests.

Table 4-3. Slug vs. One Well Steady State Hydraulic Conductivity Comparison

Well Type	Mean	Standard Deviation	F	P	Statistical Difference?
slug p1 vs ss p1			0.63	0.435	No
slug p1	0.012116	0.009809			
ss p1	0.007438	0.006244			
slug pcv vs ss pcv			0.03	0.856	No
slug pcv	0.00992	0.01021			
ss pcv	0.01143	0.0138			
slug p vs ss p			0.98	0.339	No
slug p	0.005072	0.002355			
ss p	0.00334	0.001467			
slugpnp vs sspnp			8.63	0.011	Yes
slug pnp	0.022453	0.004189			
ss pnp	0.013204	0.003824			
slug d vs ss d			1.87	0.184	No
slug d	0.023927	0.006308			
ss d	0.018867	0.000603			

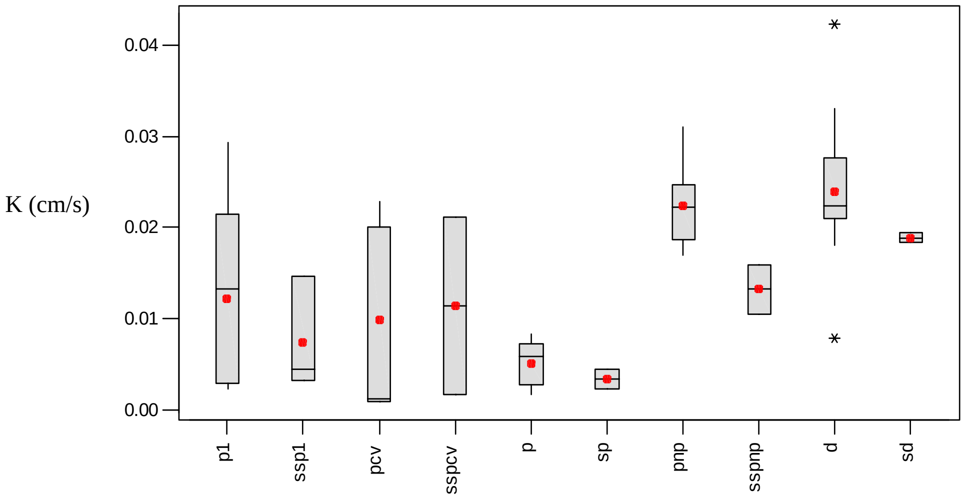
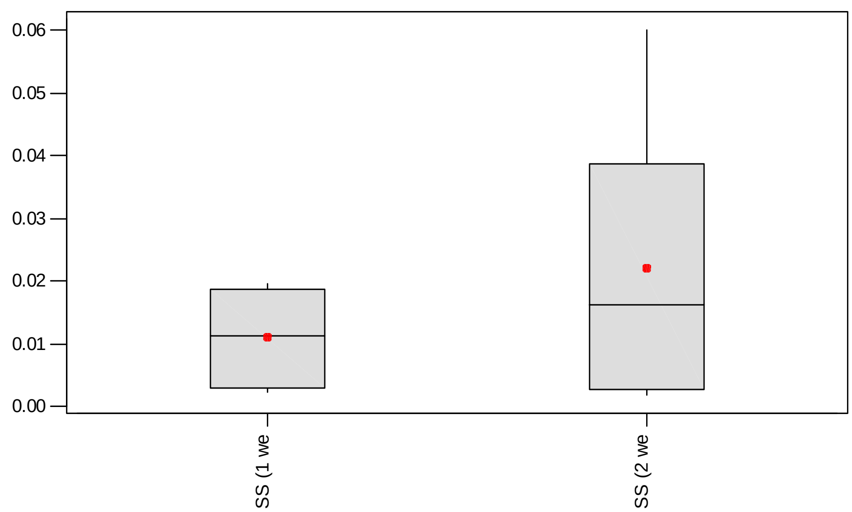


Figure 4-13. One Well Steady State K Value Data Set vs. Slug Test K Value Data Set by Well Type.

A comparative statistical analysis between one well and two well steady state values yielded no statistical difference (Figure 4-14). This implies that within the clusters tested there was little horizontal variation in the hydraulic conductivity.



One-way ANOVA: SS (1 well), SS (2 well) Comparison

```
Analysis of Variance
Source     DF        SS        MS        F        P      Stat. Diff.?
Factor      1  0.000488  0.000488     1.92    0.187      No
Error      14  0.003554  0.000254
Total      15  0.004042
                                   Individual 95% CIs For Mean
                                   Based on Pooled StdEv
Level       N      Mean     StDev  --+---------+---------+---------+----
SS (1 we    8   0.01098   0.00745   (-----------*-----------)
SS (2 we    8   0.02202   0.02127             (-----------*-----------)
                                   --+---------+---------+---------+----
Pooled StDev =   0.01593           0.000     0.010     0.020     0.030
```

Figure 4-14. Hydraulic Conductivity Comparison between 1 and 2 Well Steady State Pumping Tests

4.5 Well Construction Parameter Sensitivity Analysis

A sensitivity analysis was performed on both the steady state pumping test and the slug tests to see if changing certain well parameters would significantly affect the calculation of the hydraulic conductivity value. The well construction parameters for the

direct pushed wells are essentially fixed within a small range. On the other hand for the drilled wells one has a wider choice in selecting the construction parameters to use in calculating the hydraulic conductivity. For example, the sand pack length is different than the screened length. Furthermore, one could choose the screen diameter, the hole diameter or something in between for the effective radius of the well intake. To examine this situation well B1-5 (2” drilled well) was used. Table 4-4 shows the results of the sensitivity analysis resulting from varying the saturated screen length and intake diameter over the range in design parameters in consideration of the well construction.

Table 4-4. 2” Drilled Well Sensitivity Analysis

	Construction 1	Construction 2	Construction 3	Construction 4
Casing Diameter (in):	2	2	2	2
Saturated Intake Length (ft):	4.5	4.5	2	2
Screen Diameter or Intake Diameter (in):	8	2	8	2
Steady State Pump K value (cm/s):	1.83E-02	2.78E-02	2.86E-02	4.99E-02
Slug Test K value (cm/s):	2.38E-02	3.62E-02	3.72E-02	6.49E-02

The results show that the hydraulic conductivity can vary over a factor of three times depending on design parameters used in the analysis. The magnitude of the hydraulic conductivity varied inversely with the saturated intake length and directly with the intake diameter. It should be noted in the comparative analyses in the previous sections, the saturated intake length was taken as the sand pack and the intake diameter was taken as the borehole diameter (similar to the Construction 1 case). If the intake length had been taken as the length of the well screen and/or the intake diameter taken as somewhat less than the hole diameter, it would have magnified the differences between the drilled and direct pushed wells by an additional factor of about two times.

In all previous analyses dealing with the pushed no pack wells it was assumed that the screen diameter was the intake diameter and the screen length was the intake length.

This assumes that the formation readily collapsed around the screen section and compacted to the original formation bulk density. An analysis was conducted on well B1-1 (3/4" pushed no pack) to evaluate the extent to which the hydraulic conductivity is sensitive to these assumptions. The naturally developed wells were constructed in holes that had a 2.5" diameter. Table 4-5 shows the results of varying the intake diameter between the screen and hole diameter and also making allowance for a somewhat larger screen length.

Table 4-5. Pushed No Pack Sensitivity Analysis

	Construction 1	Construction 2	Construction 3	Construction 4
Saturated Intake Length (ft):	2	2	3	3
Saturated Intake Diameter (in):	0.75	2.5	0.75	2.5
Steady State K value (cm/s):	1.59E-02	1.13E-02	1.16E-02	8.57E-03
Slug Test K value (cm/s):	1.77E-02	1.26E-02	1.30E-02	9.55E-03

The results show that the hydraulic conductivity can vary over a factor of about two times depending on design parameters selected. If the intake diameter chosen was taken as the hole diameter instead of the screen diameter, the hydraulic conductivity values determined from the pushed no pack well would be statistically comparable to the other ¾" direct push prepack wells. If the screen length was longer the comparison would be even stronger. This of course also implies that the difference in hydraulic conductivity between the drilled wells and the pushed no pack wells would be greater.

5.0 Discussion

5.1 Interpretation of Test Results

Table 5-1 summarizes the ANOVA results.

Table 5-1. Summary of ANOVA Results

K Comparison Summary Table	K values used	Statistical Difference ?
Impact of Development on K Determinations	Slug	Varied
Induced Head Comparisons (1.3 - 1.3 ft) vs. (2.7 - 3.3 ft)	Slug	No
Slug In vs. Slug out	Slug	No
Screen Length (7.0-12.0) vs. (10.0-12.0)	Slug	Yes[1]
Prepack K Value Comparison	Slug	No
Direct Push Well Type Comparison	Slug	Yes
Pushed (P) vs. Drilled (D) Wells (Slug Data)	Slug	Yes
Pushed (P) vs. Drilled (D) K Comparison (Steady State Data)	Steady State	Yes
Drilled (D) vs. Pushed No Pack (PNP) K Comparison	Slug	No
Slug, Steady State, Unsteady State K Comparison	All	No
[1] Data sets fall within two standard deviations of one another		

5.1.1 Impact of Development on Hydraulic Conductivity

Conceivably fines could clog the prepacks and sand packs as well as the slots of the screen. Such a situation would result in lower hydraulic conductivity values. Therefore, it makes sense to conduct well development to help remove fines from the nearby formation, prepacks, and screen slots. As noted previously, there was a significant quantity of fine material at the test site that was removed by development. The test results showed mixed findings where 1/3 of the wells showed an increase, 1/3 showed a decrease, and 1/3 showed no statistically significant change in hydraulic conductivity. Interestingly enough there was no discernable variation with hydraulic conductivity as a function of development with respect to well type. Unfortunately, the wells had been previously sampled, purged, and developed prior to this study. Furthermore, our study was not initiated upon well completion. These factors complicate the interpretation of these results. For the wells whose hydraulic conductivity increased with development this is likely the result of the removal of fines from the screen,

sandpack, well bore, or formation. For the wells that did not show any discernable change this may be a result of previous development or sampling. It may also reflect fewer fines in the formation in the immediate vicinity of the wells. The wells that exhibited a decrease in hydraulic conductivity with development may result from the mobilization and redeposition of fines during the rigorous development applied in this study that clogged the formation, prepack, or well screen slots. Alternatively, the removal of fines during development may have caused some level of compaction around the well screens.

5.1.2 Influence of Induced Head on Hydraulic Conductivity

The magnitude of the induced head can impact the effective stress experienced by the formation outside the well. A slug-in test causes an increase in water pressure and results in a decrease in the effective stress in the formation in the vicinity of the well screen. This could cause formation expansion and result in an increase in formation hydraulic conductivity. On the other hand, a slug-out test causes a decrease in water pressure and results in an increase in effective stress. This might be expected to cause formation compaction and result in a decrease in formation hydraulic conductivity. The extent to which the hydraulic conductivity might be affected would depend on the relative magnitude of the initial head with respect to the water column in the well and mechanical properties of the formation (for example, formation density, degree of compaction, degree of cementation, and Young's modulus).

The induced head analysis compared hydraulic conductivity values from 48 tests where the initial induced head ranged from 0.7 to 1.3 ft to 9 tests where the induced head ranged from 2.7 to 3.3 ft. The column of water in these wells ranged from 7 to 11 ft.

Hence the higher induced heads, which ranged up to 34 % of the water column in the wells might be expected to significantly influence the effective stress in the formation outside the screens. The fact that the hydraulic conductivity values appeared to be independent of the induced head in this study maybe because of the coarse-grained nature of the material and its associated mechanical properties and the rapid dissipation of the head with time. These conditions may inhibit the formation from responding to the change in effective stress. In finer-grained materials the higher head values might be expected to have an impact on the hydraulic conductivity values. If such an impact occurred one might expect to see a change in hydraulic conductivity value as the head changed with time. This would make itself known on the log head-time curve where the slope of the log head-time curve would vary with time.

5.1.3 Comparison of Hydraulic Conductivity Values Determined by Slug-in and Slug-out Tests

Barring impacts to the effective stress as discussed above one might anticipate that the results from the slug-in and slug-out tests should be the same. This was the case here where the comparative tests yielded no statistical difference between the data sets.

5.1.4 Comparison of Hydraulic Conductivity Values Determined from Wells with Different Screen Lengths

The two primary well clusters tested in Cell B were B1 and B2. These two clusters had 10 – 12 ft and 7 – 12 ft screened intervals, respectively. An ANOVA was performed to determine if the hydraulic conductivity values from the B1 cluster could be grouped together with the hydraulic conductivity values from the B2 cluster to improve the amount the data for statistical analysis. The analysis indicated that the two clusters were not statistically comparable. However, the mean values only differed by a factor of

two and the data sets fall well within two standard deviations of one another. As such they were treated as one statistical population. This is further supported by the CPT and boring logs which show a poorly graded (well sorted) medium sand extending over the 7 to 12 foot depth interval of interest.

5.1.5 Comparison of Hydraulic Conductivities Values Determined from Prepack Wells

Three different types of prepack wells were used in this study. The two types of ¾" prepacks differed in the prepack grain size distribution. The third type differed from one of the ¾" prepacks in that the diameter was larger. Differences in hydraulic conductivity values could potentially arise owing to differences in the frictional characteristics of the prepack and screens. The finer grained, smaller diameter prepacks could potentially result in lower hydraulic conductivity values. Furthermore, the finer grained, smaller diameter prepacks may be more susceptible to clogging by fines. The ANOVA yielded no statistical difference between the prepack wells. Recall these wells were developed prior to testing and placed in a medium sand formation, hence clogging is not expected to be a significant issue here. Based on preliminary test data, the prepacks had a very high permeability on the order of 1 to 100 cm/s. As such, frictional losses would not be expected to be significant in the prepacks in the range of flow achieved in testing in this study.

5.1.6 Comparison Between Naturally Developed and Prepack Wells

Based on the ANOVA statistics, a statistical difference was found between hydraulic conductivity values obtained from the prepack wells and the naturally developed wells. A possible reason for the differences observed may relate to the annular space around the naturally developed well. The intake diameter for these wells

has been taken as the outer casing diameter. However, the wells were constructed in holes that had a larger diameter (2.5”). Upon collapse of the formation material around the screen, bridging may have occurred, and/or the disturbed formation material may have been loosened. Hence, there may a high permeable zone directly adjacent to the screen section. If this highly permeable zone was taken into account by increasing the effective intake radius of the pushed no pack wells, their calculated hydraulic conductivity values would be comparable to the average value of the direct push prepack wells (approximately 9 x 10^{-3} cm/s).

Another possible reason for the difference could relate to the hydraulic conductivity of the prepack exhibiting skin effects. As noted previously, our laboratory tests conducted on the prepacks have shown hydraulic conductivity values that are much greater than the formation hydraulic conductivities. Therefore, it is highly unlikely that they constrain flow. However, it is possible that during well development fines were lodged in the sandpack, creating a skin effect and impacting the hydraulic conductivity.

Another possible reason for the differences in the well types relates to formation heterogeneity. An analysis of the variance in hydraulic conductivity values obtained in any given well shows this variance to be very small. The average percent RSD for the individual wells was 18%. This variance was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells is largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method.

5.1.7 Comparison Between Pushed and Drilled Wells

The statistical analyses indicated that hydraulic conductivity values obtained from the 2” drilled wells were: statistically different from the 2” prepack wells; statistically comparable to the hydraulic conductivity of the pushed no pack wells; and statistically different from the prepack wells when grouped together.

The differences between the drilled and prepack wells may relate to the following conditions. It is possible during the hollow stem auger drilling formation material surrounding the hole is loosened. This could cause an increase in hydraulic conductivity.

The differences between the drilled wells and the prepack wells may relate to compaction caused during the installation of the prepacked wells. The larger diameter prepack wells required a larger diameter drive point and casing. This could have resulted in more soil compaction and thus yielded lower hydraulic conductivity values for the 2” diameter prepack wells relative to the ¾” diameter prepack wells. This is consistent with the observed difference between the prepack wells and the drilled wells. An explanation for the similarity in hydraulic conductivities between the drilled 2” and ¾” pushed no pack wells relates to the previous discussion in section 5.1.6.

Although the above explanations are feasible, it is should be emphasized that the differences in hydraulic conductivities amongst the wells are relatively small and may be a consequence of formation heterogeneity as previously discussed in section 5.1.6.

5.1.8 Comparison Between Pumping and Slug Tests

Different types of tests were performed to help address the question -- do short duration slug tests (lasting just a few seconds) provide reliable hydraulic conductivity data? Based on the statistical analyses, the slug test results in this study were comparable to the steady and unsteady test results.

Several models were used to analyze the unsteady state pumping tests. These were: the confined Theis model, the unconfined Neuman partial and fully penetrating models, and the unconfined Theis partial and fully penetrating models. A sensitivity analysis was performed to analyze the degree to which the model chosen influences the hydraulic conductivity. It was found that the results were insensitive to the model chosen. The lack of sensitivity may be the result of the short distance between the pumping and observation well and the short duration of the tests.

Table 5-2 summarizes the duration of the slug tests observed in this study. It should be emphasized that most of the tests lasted less than 20 seconds and half of the tests lasted less than 3.5 seconds. The fact that slug tests could be performed here was largely due to the performance of the pneumatic slug test kit. The critical features here were the high frequency response of the pressure transducer and the valve system, which permitted introduction of a virtually instantaneous slug. The tests here also demonstrate that steady state tests can be used as an alternative in deriving the hydraulic conductivity in high permeable formations.

Table 5-2. Slug Test Duration Summary Statistics (seconds)

Mean	17.25
Median	3.5
Minimum	0.53
Maximum	250.5

5.1.9 Deviations of Head Recovery Curves from Ideality

Often the head responses during recovery did not exhibit an ideal head versus time response. Figure 5-1 shows an ideal response curve where the recovery is exponential with time following the start of the test. Figures 5-2 to 5-5 illustrate the types of non-ideal responses observed. These were: a momentary delay before recovery; a double straight-line recovery, an oscillation during recovery; and an oscillation after recovery (under dampened response). These non-ideal effects made choosing the log linear portion of the curves problematic and somewhat subjective. The calculation of hydraulic conductivity from slug test data (with the exception of the well that exhibited oscillation after recovery) used the slope of a portion of the log linear head versus time curve. The use of the slope to some extent helps remove errors associated with identifying the initial head drop when tests behaved in a non-ideal fashion.

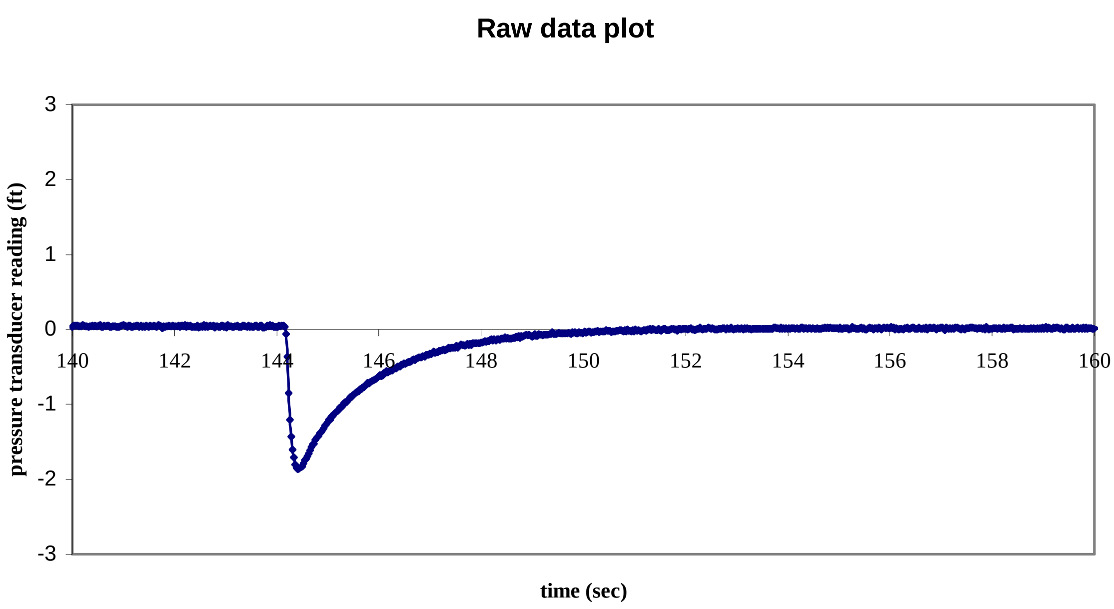


Figure 5-1. Ideal Head vs. Time Recovery Curve (Well B1-1, Post Development)

The momentary delay in recovery may be attributed to the opening rate of the release valve relative to the rate of recovery (Figure 5-2). The release valve is a ball valve that is opened by hand. If the opening rate is long relative to the rate of recovery the headspace pressure will not be dissipated instantaneously. If the rate of headspace pressure dissipation is equivalent to the rate of water level response in the well there will be a momentary delay in the pressure transducer response until the air pressure has returned to atmospheric.

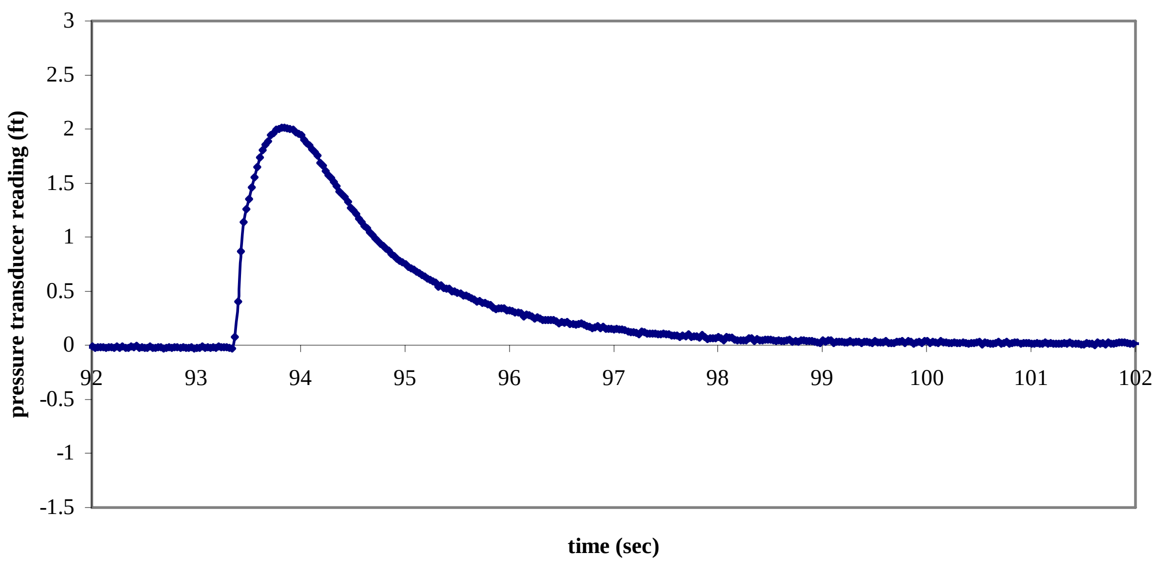


Figure 5-2. Momentary Delay in Recovery (B13 Post Development)

The response exhibited in Figure 5-3 results in a double straight-line log head versus time recovery curve. Such curves have been reported in the literature. Bouwer (1989) attributed this effect to dewatering of the sandpack. He also noted that if the sandpack is not dewatered and the effect still occurred it might be due to leakage around the casing or grouting above the sandpacked zones. It is important to note that in this study the tests were designed to maintain saturated screen and sandpack intervals.

An alternative explanation for the double straight-line effect may be due to the screened interval intersecting layers of very different hydraulic conductivities. Consider two layers of different hydraulic conductivities intersecting the screened interval. The rate of recovery will be a time weighted average reflecting the hydraulic conductivities of the two layers. In early time the slope of the recovery curve will be weighted towards the higher hydraulic conductivity layer. In later time the slope of the recovery curve will be more weighted toward the lower permeable unit and its slope will be less.

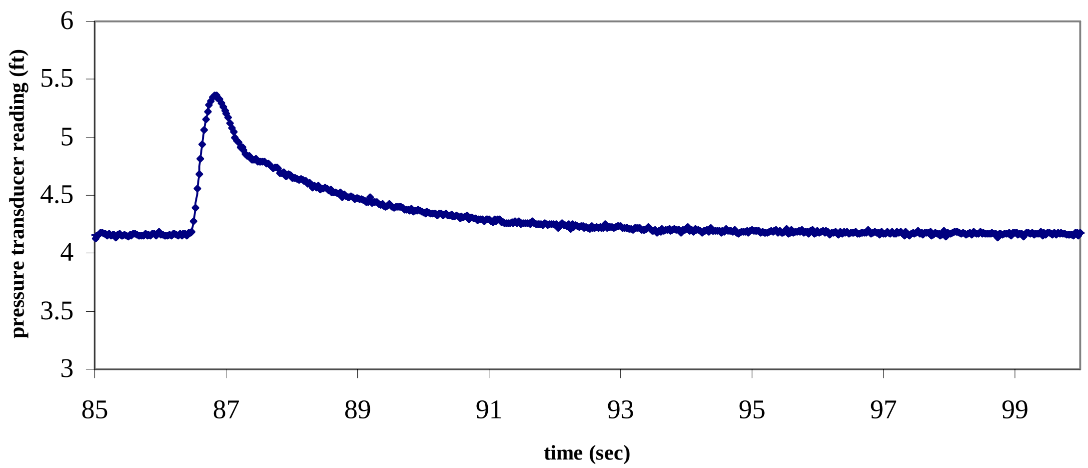


Figure 5-3. Double Straight Line Recovery (B2-2 Post Development)

B22, a ¾" pushed ASTM design prepack, exhibited an oscillatory response during the recovery of a slug-in test (Figure 5-4). This effect was reproducible and magnified with development. It is possible that the effect can be attributed to leakage in a casing joint above the water table where the water leaks into a highly permeable unit. During early time, the recovery curve maybe influenced by the rate of leakage from the casing until the water passes below the leakage point. The oscillation results from an under dampened response where the water oscillates near the leakage point. This oscillation maybe brought about by water leaking in and out of the casing joint until the head inside

and outside of the well have equilibrated. The water then continues to decline back to the static level.

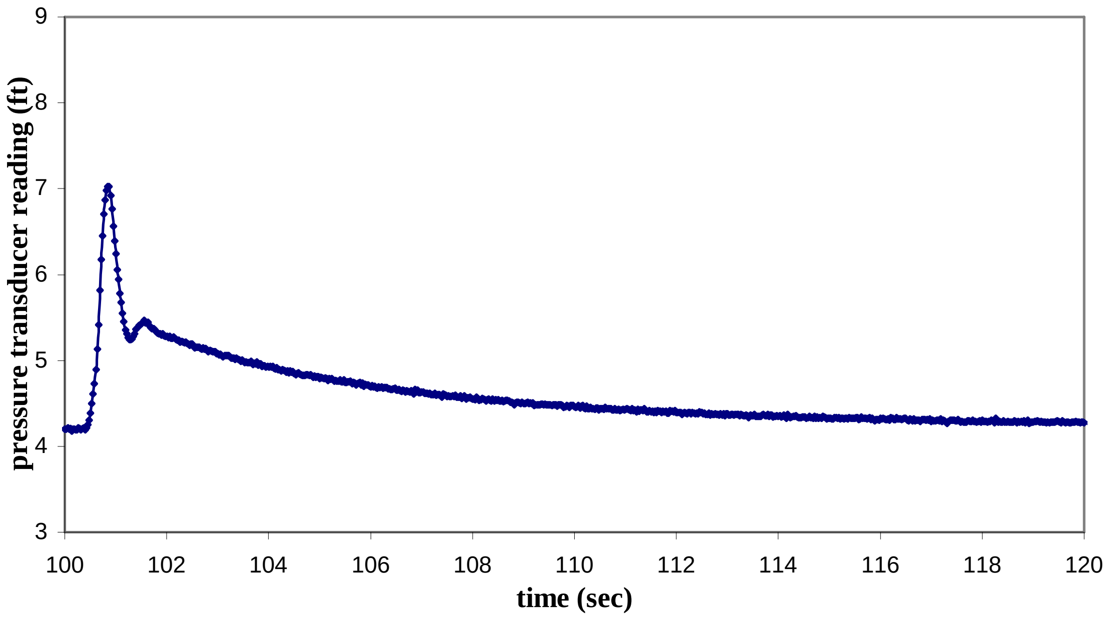


Figure 5-4. Oscillation Before Recovery (B2-2 Post Development)

An oscillation after recovery (under dampened response) was only observed in B4-6, a 3/4” pushed ASTM Design Prepack (Figure 5-5). This can be attributed to the very high hydraulic conductivity surrounding the well bore. Of the wells tested, B4-6 is the deepest screened well (12.5 to 17.5 ft). Based on the boring log, the screened interval lies within a coarse-grained sand and gravel. This well provided an opportunity to compare hydraulic conductivity values determined by using a slug test solution for an oscillatory response (Butler and Garnett, 2000) with a steady state pumping test. The results were essentially the same, differing by only 11%.

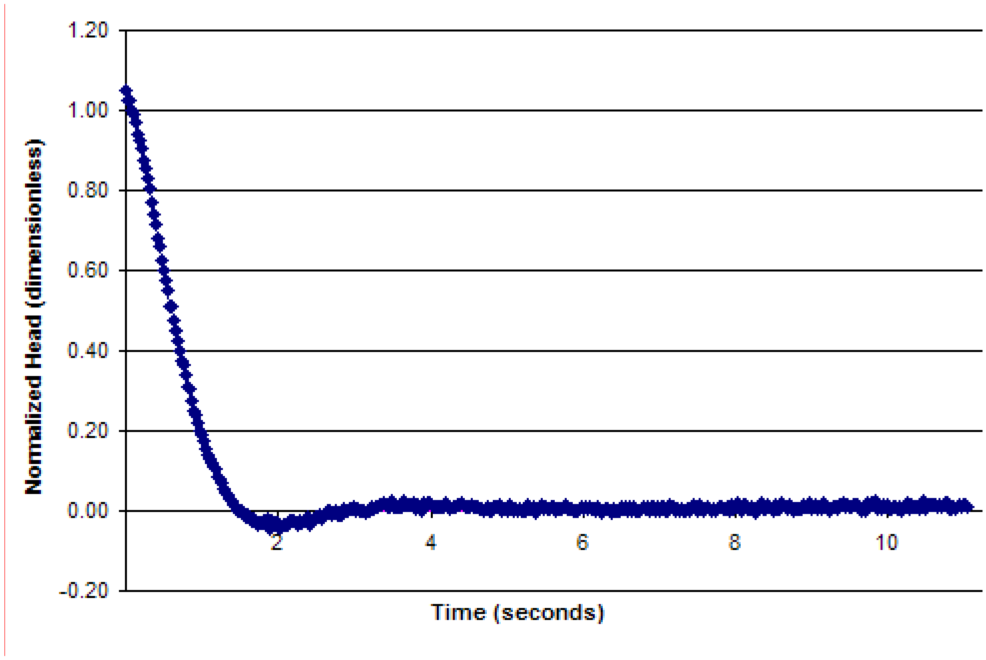


Figure 5-5. Oscillatory Recovery (B4-6)

5.2 Sources of Error in the Hydraulic Conductivity Tests

The sources of error in the hydraulic conductivity tests relate to: (1) the models chosen for analyzing the data; (2) the choice of construction parameters for the intake length, intake diameter, and casing diameter; and (3) measurements of head, time, observation well distances and discharge, for the different test types.

Three models for analyzing hydraulic conductivity were used in the tests. All of the slug tests used the Hvorslev ellipsoidal source model. This model assumes that the screened section is within a uniform material and the head distribution around the screened section is ellipsoidal in nature. These calculations did not take into account any anisotropy (ratio of horizontal to vertical hydraulic conductivity). As the anisotropy increases the results from these tests would be weighted toward a measure of horizontal hydraulic conductivity. This same model was also used for the one well steady state tests. The two well steady state tests used the Thiem model, which assumed radial flow to the pumping well within the screened the interval. Despite the differences in models

the results were essentially the same. The unsteady state tests used the Theis equation, which has the same assumptions as the Thiem equation in terms of radial flow and the hydraulic conductivity results between the models were also essentially equivalent.

In all the tests performed a potential source of error relates to the choice of model input parameters (the construction parameters, which are the intake length, intake diameter, and casing diameter). The error in the casing diameter is relatively negligible. This would also hold true for the prepack wells and the naturally developed wells where the well screens and the sandpack lengths are equivalent and may be taken as the intake length. The intake diameter on the other hand for these wells and the conventional hollow stem auger wells may range from the actual screened diameter to the hole diameter and can introduce errors up to a factor of 3 times.

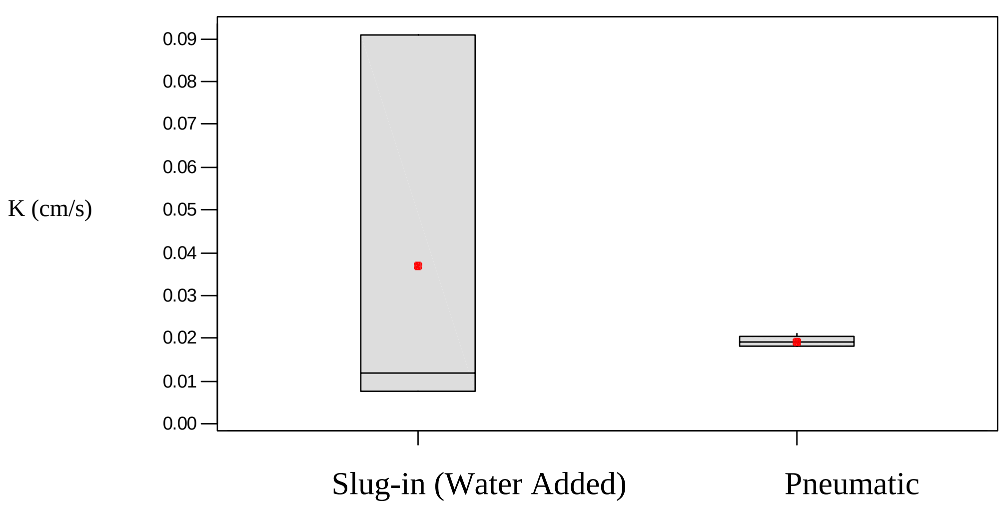
The pressure transducers can readily measure head to within several thousandths of a foot. The Geoprobe® pressure transducer used in the slug tests sampled at rates of 10 and 38 Hz. In the steady state two well tests the In Situ MiniTroll pressure transducer was used at a sampling rate of 2 Hz. The errors associated with the head and time readings are considered negligible. The discharge was calculated in the steady state pump tests by measuring the volume of water discharged in a given time period. Sufficient quantities of water were collected for each test to assure that the error in volume determination and collection time was negligible. For each test the discharge was measured three times. Discharge measurements had a reproducibility of better than 0.5 % RSD.

5.2.1 Propagation of Error

To quantify the slug test error a propagation of error calculation was performed (Appendix A). Well B1-1 was randomly selected from the wells tested for the purpose of the calculation. To perform the calculation errors were estimated for the input parameters. The propagation of error was determined to be ±6.96 x 10^{-4}. This error is two orders of magnitude smaller than the average post hydraulic conductivity value of 2 x 10^{-2} cm/s for the well. Recall each slug test was conducted in at least triplicate. As a measure of test precision an average RSD was computed for all post development slug tests and was found to be 18%.

5.3 Comparison of Test Results to Previous Studies

Prosser (1981) performed a study in which he compared both pneumatic and traditional slug-in tests. To statistically compare his data an ANOVA was conducted in this study. Figure 5-6 shows that the data is statistically comparable.

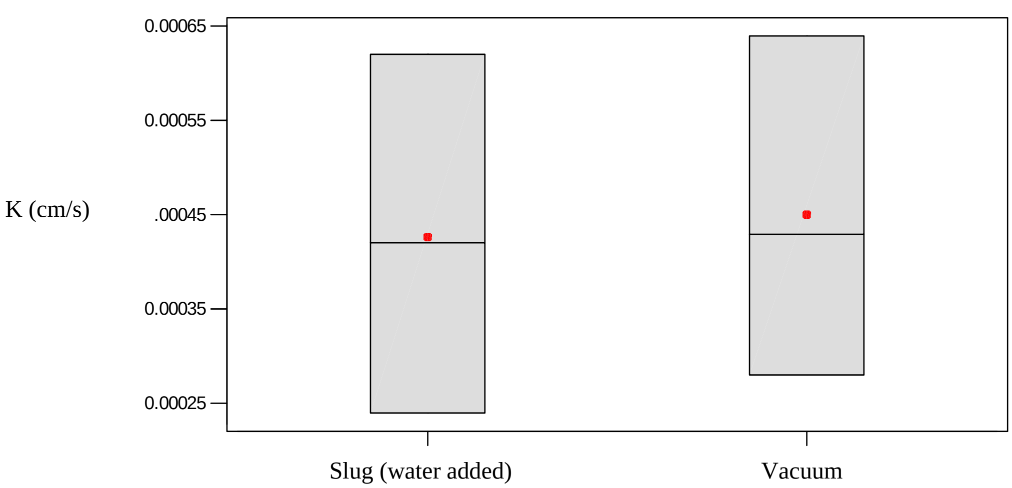


One-way ANOVA: Slug In (Water Added), Pneumatic

```
Analysis of Variance
Source     DF        SS        MS        F        P      Stat.Diff.?
Factor      1  0.000585  0.000585     0.80    0.407      No
Error       6  0.004412  0.000735
Total       7  0.004997
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
Slug In     3   0.03687   0.04693      (---------------*--------------)
Pneumati    5   0.01920   0.00130   (-----------*-----------)
                                   -----+---------+---------+---------+-
Pooled StDev =  0.02712               0.000     0.025     0.050     0.075
```

Figure 5-6. Slug in vs. Pneumatic Test Hydraulic Conductivity Comparison

Orient, Nazar, and Rice (1987) compared hydraulic conductivity determinations from traditional slug-in tests to those obtained from their version of the pneumatic slug test system. Figure 5-7 shows an ANOVA of their data, which indicates the hydraulic conductivities yielded from the slug-in tests and the vacuum pneumatic tests were statistically comparable.



Analysis of Variance of Orient, Nazar, and Rice data, 1987.

```
Source     DF        SS        MS        F        P     Stat. Diff.?
Factor      1 0.0000000 0.0000000     0.02    0.885     No
Error       4 0.0000001 0.0000000
Total       5 0.0000001
Individual 95% CIs For Mean
Based on Pooled StDev
Level              N      Mean     StDev  ----+---------+---------+---------+--
Slug (water added) 3  4.27E-04  1.90E-04  (--------------*--------------)
Vacuum Test        3  4.50E-04  1.81E-04    (--------------*-------------)
----+---------+---------+---------+--
Pooled StDev = 1.86E-04             0.00020   0.00040   0.00060   0.00080
```

Figure 5-7. Hydraulic Conductivity Comparison of Traditional Slug-in and Pneumatic Vacuum Slug in Tests

McLane et al (1990) developed a pneumatic method for conducting rising and falling head tests in highly permeable aquifers. The highly permeable material in which the tests were conducted had hydraulic conductivities that ranged from 10^{-3} to 10^{-1} cm/s, which is a similar range to that found at Port Hueneme. An important finding in their study was that the release valve, which evacuates the well bore, must be equal to or greater than the well bore diameter in order to initiate an instantaneous slug. Their study compared hydraulic conductivity values obtained from pneumatic slug-in and slug-out tests at a site in Michigan and another in Nebraska. At each site a well was tested six times with each method. At the Michigan test site the results were statistically comparable within a 95% confidence interval. At the Nebraska test site they were not statistically comparable, yet their range was very small (8.53×10^{-3} to 8.94×10^{-3} cm/s for the falling head compared to 7.32×10^{-3} to 7.98×10^{-3} cm/s for the rising head). McLane et al. attributed the statistical difference to the high precision of the pneumatic test system. In this study the pneumatic system also had very high precision. However, no statistical difference was found between the slug-in and slug-out tests.

Butler and Healey (1998) found that hydraulic conductivity estimates from pumping tests were greater than slug tests in the same formation. Their paper cites

multiple sources in which, on average, slug tests yielded lower hydraulic conductivity values than pumping tests. Although one can interpret this difference as being due to an underlaying scale dependence in hydraulic conductivity, Butler and Healey attribute this observation to artifacts introduced by well installation and development. In this study there was no statistical difference between any of the test methods. This finding further supports the contention of Butler and Healey. The wells in this study were subject to rigorous well development, the well construction was highly controlled, and the well construction parameters (model input parameters) were known. Furthermore, unlike other studies, this study provided an opportunity to repeatedly test a significant number of wells and to gain an adequate level of data for a more thorough statistical evaluation.

Henebry and Robbins (2000) found in a study of direct push wells that hydraulic conductivity values increased 3.2 to 9.6 times after development. Their study found the greatest increase in hydraulic conductivity occurred after the first development round. It was concluded in their paper that only after well development could an accurate measure of hydraulic conductivity be obtained in direct push wells. In this study we used the same development technique and also found that the hydraulic conductivity, if it did change, changed most significantly following the first round of development. However, not all wells in this study exhibited an increase in hydraulic conductivity following development. Of the 15 wells tested, 5 exhibited no significant change in hydraulic conductivity with development, 5 wells showed an increase, and 5 wells showed a decrease. The increase in hydraulic conductivity ranged from 1.2 to 2.1 times, while the decreased ranged from 1.6 to 3.6 times. The differences observed in this study relative to Henebry and Robbins' are most likely due to prior development, purging, and sampling

conducted at the Port Huememe wells. Perhaps even more important is that the wells tested in Henebry and Robbins had a much lower hydraulic conductivity than those tested in this study. Their wells were constructed in glacial till with a significant level of fines. The till relative to the medium to coarse sands and gravel at the Port Hueneme site were likely more susceptible to formation compaction during well installation and clogging of screens (i.e. skin effects).

Butler et al (2002a) conducted at comparative study of hydraulic conductivity values obtained from steady state pumping tests between direct push and conventional wells. The tests were conducted in a coarse sand and gravel aquifer. The hydraulic conductivity values were in very good agreement (within 4%). Also, steady state hydraulic conductivity values obtained were within 12% of multilevel slug tests in a nearby well. These results are in good agreement with the results in this study in a similar highly permeable environment.

BP and EPA (2002) conducted a study at four sites comparing hydraulic conductivity values determined from direct push and conventional HSA wells. The hydraulic conductivity at the sites ranged from approximately 10^{-6} to 10^{-2} cm/s. All the direct pushed wells were naturally developed (PNP). Based on a statistical analysis of a limited number of factors that could influence the comparison of hydraulic conductivity values between well types, they report that the only statistically significant factor found was well type. On average the hydraulic conductivity was approximately 4.4 times larger for the conventional wells than for direct push wells. In their explanation for these results they note the wells may not have been properly developed. Furthermore, their conductivity values had a large variance. For example, they report that the hydraulic

conductivity values often varied by more than a factor of two for the same well tested on different dates. Other factors that may have influenced their results include backfill zone drainage, choice of input parameters (especially the screened length and well radius for the conventional wells), and the method used to analyze the test data.

In contrast to the BP and EPA study, the hydraulic conductivity values for conventional wells in this study were very comparable to those obtained from the naturally developed (pushed no pack) direct push wells (PNP). This contrast may be due to the factors previously cited that may have influenced the BP and EPA results and the results observed in this study.

In a study by Salanitro et al. (2000) they cite hydraulic conductivities at the Port Hueneme site to be in the range of 6×10^{-2} to 1.4×10^{-1} cm/s. Additionally, Amerson and Johnson (2003) conducted a natural gradient tracer test at the Base. The test was conducted up gradient from the test site in this study. They computed hydraulic conductivities based on the tracer test to range from 2×10^{-3} to 4.5×10^{-1} cm/s. The hydraulic conductivity values in this study resulted in a range from 2×10^{-3} to 4.2×10^{-2} cm/s. These are in close agreement with the other tests in consideration of the narrow vertical depth interval tested in this study.

5.4 Applicability of Findings

This research has shown that short duration pneumatic slug tests are statistically comparable to pumping tests conducted in the same wells. As such, application of pneumatic slug testing offers a means to save on time, effort, and cost of conducting pumping tests especially in highly permeable, contaminated environments. Furthermore, the pneumatic tests allow you to readily repeat tests, which is ideal for developing test

statistics. Hydraulic conductivity values obtained from testing direct push and conventional wells were similar, although statistical differences amongst different well types were found. From a practical perspective both types of wells appear suited for conducting hydraulic conductivity tests provided they are screened (including the sandpack) below the water table and they are well developed. However, there are clearly cost advantages involved with the installation of small diameter direct push wells. The complexities involved in analyzing oscillatory well responses may be circumvented through analyzing steady state pumping tests, although issues associated with the disposal of water arise. It should be noted that the spreadsheet analysis method by Butler and Garnett (2000) provides a means to analyze the oscillatory response in a relatively straightforward manner. The hydraulic conductivity values derived from this approach agree quite closely with steady state pumping test results.

One of the key objectives of this study was to evaluate whether there was a systematic means to equate the results from conventional wells to those of the direct push wells, assuming significant statistical differences were found. Given the results (similar hydraulic conductivities and the strong possibility that variations observed are because of formation heterogeneity), it would appear that such a relationship is not necessary.

Butler et al (1996) and Henebry and Robbins (2000) recommended a series of practices designed to improve slug test methodology. The results here would reinforce their guidance. Of particular importance with respect to pneumatic slug testing are the following: (1) three or more tests should be done at any given well to determine reproducibility; (2) attention should be paid to proper well design (especially having the screened section fully submerged during testing) and well development; (3) care must be

taken in choosing the appropriate portion of the log head versus time curve for analysis; (4) high frequency data acquisition pressure transducers should be used in conducting tests in highly permeable wells; (5) use of vacuum-pressure pumps permits conducting slug-in, in addition to slug-out, tests in a very controlled, highly reproducible manner; and (6) spreadsheet templates should be developed to aid in data management and analysis.

5.5 Recommendations for Future Research

Based on the results of this study, the following are recommendations for future research:

1. Ideally the comparative tests conducted here would have been enhanced if there were more well clusters all screened over the same depth interval. This would help reduce ambiguities, increase the data for statistical analysis, and permit an assessment of the degree of spatial heterogeneity by examining how the hydraulic conductivities vary for a given well type.
2. It would also be valuable to have wells developed and tested immediately following installation.
3. To examine the impact of scale on the determination of the hydraulic conductivity value, two well steady state pumping tests should be conducted. For example, using one well as the pumping well and having multiple observation wells at different distances, one can evaluate how the hydraulic conductivity varies spatially and with distance for comparison to the slug test results.
4. It would be useful to conduct testing at several locations having widely different hydraulic conductivities. These tests would help evaluate the extent to which

hydraulic conductivity values determined in wells in different formation types are sensitive to well installation and development.

6.0 Conclusions

- Short duration pneumatic slug tests were determined to be a viable approach for determining hydraulic conductivity values in a high permeable formation. The results of a statistical comparison between the pneumatic slug tests lasting only a few seconds and the steady state pumping tests yielded no statistical difference.
- Hydraulic conductivity values in direct push prepack wells were found to be independent of prepack design, well radius, induced head, and test method (assuming the same screened interval).
- The hydraulic conductivity values determined from the different well types in the B1 and B2 clusters had a mean post development value of 2×10^{-2} cm/s and a standard deviation of 8×10^{-3}. The ANOVA analysis indicated there was no statistical difference amongst the prepack wells. Furthermore, there was no statistical difference between the pushed no pack wells and the drilled wells. However, the ANOVA analysis indicated that there was a statistical difference between the latter wells and the prepack wells. The variance associated with hydraulic conductivity tests in individual wells was many times smaller than the variance computed using the average hydraulic conductivity values from wells of the same type. This implies that the differences in hydraulic conductivity values observed amongst the wells is largely due to formation spatial heterogeneity rather than differences in well construction and installation, or test method.
- Although development had an impact on the hydraulic conductivity for most of the wells, the impact was ambiguous. Of the 15 wells tested 10 wells had statistical differences in hydraulic conductivity between pre and post

development. Of the 10 wells, 5 wells showed increases in hydraulic conductivities and 5 well showed decreases.

- Unsteady state, steady state pump tests, and pneumatic slug tests were shown to be statistically comparable means of determining hydraulic conductivity analysis in highly permeable formations.

References

Amerson, I, R. L. Johnson. 2003. Natural Gradient Tracer Test to Evaluate Natural Attenuation of MTBE Under Anaerobic Conditions. Ground Water Monitoring and Remediation, v. 23, no. 1: 54-61.

American Society for Testing and Materials. 1990. Standard Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers (D 5092-90), p. 996-1009.

American Society for Testing and Materials. 1996. Standard Test Method (Field Procedure) for Instantaneous Change in Head (Slug) Tests for Determining Hydraulic Properties of Aquifers (D 4044-96), p. 473-475.

American Society for Testing and Materials. 2001a. Standard Guide for Installation of Direct Push Ground Water Monitoring Wells (D6724-01).

American Society for Testing and Materials. 2001b. Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers (D6725-01).

AQTESOLV® for Windows 95/98/NT, Version 3.01 – Student, Copyright© 1996-2000, HydroSOLVE, Inc.

Binkhorst, G.K., and Robbins, G.A., 1994, A Review and Assessment of Factors Affecting Hydraulic Conductivity Values Determined From Slug Tests, USEPA rept. EPA\600\R-93\202, 67.

Binkhorst, G.K., G. A. Robbins. 1998. Conducting and Interpreting Slug Tests in Monitoring Wells and Partially Submerged Screens. Ground Water. March-April 1998, v. 36, no. 2, pp. 225-229.

Bouwer, Herman. 1989. The Bouwer and Rice Slug Test – An Update. Ground Water. v. 27, no. 3, pp. 304-309.

Bower, H., R. C. Rice. A Slug Test For Determining Hydraulic Conductivity Of Unconfined Aquifer with Completely Or Partially Penetrating Wells. Water Resources Research. June 1976, v. 12, no. 3, pp. 423- 428.

BP Corporation North America Inc., and The Underground Storage Tank (UST) Programs of U.S. Environmental Protection Agency, Region 4, Atlanta, GA and Region 5, Chicago, IL. Monitoring Well Comparison Study: An Evaluation of Direct-Push Versus Conventional Monitoring Wells. 1 May 2002.

Bulter, J.J. Jr., Garnett, E.J. 2000. Simple Procedures for Analysis of Slug Tests in Formations of High Hydraulic Conductivity using Spreadsheet and Scientific Graphics Software. KGS Open File Report 2000-40. December 2000.

Butler Jr., J. J, C. D. McElwee, and W. Liu. 1996. Improving the quality of parameter estimates obtained from slug tests. Ground Water. May-June 1996, v. 34, no. 3, pp. 480-490.

Butler Jr., J.J. 1996. Slug Tests in Site Characterization: Some Practical Considerations. Environmental Geosciences. v. 3, no. 2, pp. 154-163.

Butler Jr., J.J. 2002. A simple correction for slug tests in small-diameter wells. Ground Water. v. 40, no. 3, pp. 304-307.

Butler Jr., J.J., J. M. Healey. 1998. Relationship between pumping-test and slug-test parameters: Scale effect or artifact? Ground Water. March-April 1998, v. 36, no. 2, pp. 305-313.

Butler Jr., J.J., J. M. Healey, G. W. McCall, E. J. Garnett, and S. P. Loheide II. 2002a. Hydraulic tests with direct-push equipment. Ground Water, v. 40, no. 1, pp. 25-36.

Butler, Garnett, Healey, 2002b, Analysis of Slug Tests in Formations of High Hydraulic Conductivity, Ground Water, Sept 2002.

Butler, J. J. Jr. The Design, Performance, and Analysis of Slug Tests. Boca Raton, Lewis Publishers, 1997.

Ferris, J. G. and D. B Knowles. 1954. The Slug Test for Estimating Transmissibility. Ground Water Notes Hydraulics. No. 26, November 1954, pp. 1-7.

Geoprobe® Pneumatic Slug Test Standard Operating Procedure, Technical Bulletin No. 19344, February 2002.

Geoprobe® Website. Graphics obtained from www.geoprobe.com.

Havlicek, L and Crain, Ronald D. Practical Statistics for the Physical Sciences. American Chemical Society, Washington, D.C. 1988.

Henebry and Robbins, Reducing the Influence of Skin Effects on Hydraulic Conductivity Determinations in Multilevel Samplers Installed with Direct Push Methods, 2000.

Hopkins, Will G. 2002. Sportscience Website. A New View of Statistics. www.sportsci.org/resource/stats/pvalues.html.

Houser, Thomas, Donald R. Schreiber and George G. Lowry. Physical Chemistry Laboratory, 1992 Revised and Reprinted SEP-1992. Department of Chemistry, Western Michigan State University, Kalamazoo, Michigan.

Hvorslev, M.J., 1951. Time Lag and Soil Permeability in Groundwater Observations. U.S. Army Corps of Engineers Waterways Experiment Station. Bull. 36, pp 1-50.

Kipp, K. L. Jr. Type Curve Analysis of Inertial Effects in the Response of a Well to a Slug Test. Water Resources Research. September 1985, v. 21, no. 9, pp. 1397-1408.

Kram, Mark et al. NFESC Technical Report TR-2120-ENV. Performance Comparison Direct-Push Wells Versus Drilled Wells. January 2001.

Leap, Darrell I. 1984. A Simple Pneumatic Device and Technique for Performing Rising Water Level Slug Tests. Ground Water Monitoring Review, Fall 1984, 141-146.

Levy, B. S., L. Pannell. 1991. Evaluation of a Pressure System for Estimating In-situ Hydraulic Conductivity. National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods (5^{th} : 1991 : Las Vegas, NV). pp. 31-46.

McLane, G. A., D. A. Harrity, K. O. Thompsen, Ph.D., P.G. 1990. A Pneumatic Method for Conducting Rising and Falling Head Tests in Highly Permeable Aquifers. National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods (4^{th}: 1990: Las Vegas, NV). pp. 1219-1231.

McElwee, C.D. and Zenner, M., Unified analysis of slug tests including nonlinearities, inertial effects, and turbulence, *Kans. Geol. Surv. Open-File Rep.* 94-45. 1993.

Microsoft® Excel 2000, Copyright 1985-1999.

Miller, J.C. and Miller, J.N. Statistics for Analytical Chemistry. Ellis Horwood, 1993.

MINITAB® Release 13.0, Help Section, State College, PA

Monitoring Well Comparison Study: An Evaluation of Direct-Push Versus Conventional Monitoring Wells. 2002. BP Corporation North America Inc. & UST Program of U.S.E.P.A, Region 4 & 5. May 1, 2002.

Neuman, S. P. , 1974. Effect of Partial Penetration on Flow in Unconfined Aquifers Considering Delayed Gravity Response, Water Resouces Research, vol. 10, no. 2, pp. 303-312.

Orient, J.P., A. Nazar, and R.C. Rice, 1987. Vacuum and Pressure Test Methods for Estimating Hydraulic Conductivity. Ground Water Monitoring Review. Winter 1987, pp. 49-50.

Prosser, Donald W. 1981. A Method of Performing Response Tests on Highly Permeable Aquifers. Ground Water. v. 19 (6), pp. 588- 592.

Robbins, G. 2000. Expedited Site Assessment: The CD, Connecticut Department of Environmental Protection.

Salanitro, J. P., P. C. Johnson, G. E. Spinnler, P. M. Maner, H. L. Wisniewski, and C. Bruce. 2000. Field-Scale Demonstration of Enhanced MTBE Bioremediation through Aquifer Bioaugmentation and Oxygenation. Environmental Science and Technology, v. 34, 4152-4162.

Skoog, Douglas et al. Analytical Chemistry: An Introduction. 7th Edition. 2000. Saunders College Publishing.

Theim, G. 1906. Hydrologische methoden. Leipzig: Gebhardt.

Texasoft Website. 2003. http://www.texasoft.com/pvalue.html - statistical information help.

van der Kamp, G. 1976. Determing Aquifer Transmissivity by Means of Well Response Tests: The Underdamped Case. Water Resources Research, v. 12, no. 7, p71-77.

Zlotnik, Vitaly A., V. L. McGuire. 1998. Multi-level Slug Tests in Highly Permeable Formations: 1. Modification of Springer-Gelhar (SG) Model. Journal of Hydrology. v. 204, pp. 271-282.

Zlotnik, Vitaly A., V. L. McGuire. 1998. Multi-level Slug Tests in Highly Permeable Formations: 2. Hydraulic Conductivity Identification, Method Verification, and Field Applications. Journal of Hydrology. v. 204, pp. 283-296.

Appendix A

Propagation of Error Calculation

To quantify the slug test error a propagation of error calculation was performed. Well B11 was randomly selected from the wells tested. The hydraulic conductivity is calculated based on Equation 3-2, assuming the following errors in the input parameters.

slope = log change in head / change in time
D_r = corrected casing diameter
L = saturated intake length
D = intake diameter

slope ± 0.09985
D_r ± 0.0001 ft
L ± 0.3 ft
D ± 0.01 ft

Equations:

$$If \ldots z = \frac{x}{y}, \varepsilon_z = \frac{x}{y} \cdot \sqrt{\left(\frac{\varepsilon_x}{x}\right)^2 + \left(\frac{\varepsilon_Y}{y}\right)^2}$$

$$If \ldots z = x^a, \varepsilon_z = (a \cdot x^{a-1}) \cdot \varepsilon_x$$

$$If \ldots z = a + x, \varepsilon_{\backslash z} = \varepsilon_x$$

$$If \ldots z = x \pm y, \varepsilon_z = \sqrt{\varepsilon_x{}^2 + \varepsilon_y{}^2}$$

$$If \ldots z = LOG_{10} x, \varepsilon_z = 0.434 \frac{\varepsilon_x}{x}$$

$$If \ldots z = a \cdot x, \varepsilon_z = a \cdot \varepsilon_x$$

$$If \ldots z = x \cdot y, \varepsilon_z = (x \cdot y) \cdot \sqrt{\left(\frac{\varepsilon_x}{x}\right)^2 + \left(\frac{\varepsilon_y}{y}\right)^2}$$

Calculations: For well B11

$$\frac{L}{D} = \varepsilon 1 = \frac{2}{0.21} \cdot \sqrt{\left(\frac{0.3}{2}\right)^2 + \left(\frac{0.01}{0.21}\right)^2} = 1.4988$$

$$\left(\frac{L}{D}\right)^2 = \varepsilon 2 = \left(2 \cdot \left(\frac{2}{0.21}\right)\right) \cdot 1.4988 = 28.54857$$

$$1 + \left(\frac{L}{D}\right)^2 = \varepsilon 3 = \varepsilon 2 = 28.54857$$

$$\sqrt{1 + \left(\frac{L}{D}\right)^2} = \varepsilon 4 = 0.5 \left(\frac{1}{\sqrt{\left(\frac{2}{0.21}\right)^2}} \right)^{(-0.5)} \cdot 28.54857 = 1.4906$$

$$\left(\frac{L}{D} + \sqrt{1 + \left(\frac{L}{D}\right)^2}\right) = \varepsilon 5 = \sqrt{1.49883^2 + 1.490636^2} = 2.113879$$

$$LOG \cdot \left(\frac{L}{D}\right) + \sqrt{1 + \left(\frac{L}{D}\right)^2} = \varepsilon 6 =$$

$$0.434 \cdot \left(\frac{2.113879}{\left(\frac{2}{0.21}\right)} \right) + \left(1 + \sqrt{+\left(\frac{2}{0.21}\right)^2} \right) = 0.0480$$

$$5.304 \cdot LOG \cdot \left[\left(\frac{L}{D}\right) + \sqrt{1 + \left(\frac{L}{D}\right)^2} \right] = \varepsilon 7 = 5.304 \cdot (0.083653) = 0.443697$$

$$D_r^{\,2} = \varepsilon 8 = (2 \cdot 0.0596) \cdot 0.0001 = 1.192 \times 10^{-5}$$

$$-slope \cdot {D_r}^2 \cdot 5.304 \cdot LOG\left[\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right] = \varepsilon 9 = 0.192117 \cdot 0.0596^2 \cdot 5.304 \cdot$$

$$LOG\left(\frac{0.117237}{\left(\frac{2}{0.21}\right)} + \left(\sqrt{1+\left(\frac{2}{0.21}\right)^2}\right)\right) \cdot$$

$$\sqrt{\left(\left(\frac{0.09985}{0.192117}\right)^2 + 5.304 \cdot LOG\left(\frac{0.117237}{\frac{2}{0.21} + \left(\sqrt{1+\left(\frac{2}{0.21}\right)^2}\right)}\right)\right)^2}$$

$$= 1.191518 \times 10^{-3}$$

$$8L = \varepsilon 10 = 8 \cdot 0.3 = 2.4$$

$$\frac{-slope \cdot {D_r}^2 \cdot 5.304 \cdot LOG\left[\frac{L}{D} + \sqrt{1+\left(\frac{L}{D}\right)^2}\right]}{8L} = \varepsilon 11 =$$

$$\frac{0.192117 \cdot 0.0596^2 \cdot 5.304 \cdot LOG\left(\frac{0.117237}{\frac{2}{0.21} + \sqrt{1+\left(\frac{2}{0.21}\right)^2}}\right)}{8 \cdot 2} \cdot$$

$$\sqrt{\left[\frac{1.915817 \times 10^{-3}}{\left(0.192117 \cdot 0.0596^2 \cdot 5.304 \cdot LOG\left(\frac{0.117237}{\frac{2}{0.21} + \sqrt{1+\left(\frac{2}{0.21}\right)^2}}\right)\right)^2} + \left(\frac{2.4}{8 \cdot 2}\right)^2\right]} = 6.96 \times 10^{-4}$$

Spreadsheets and Other Files on Disk

Appendix B – Spreadsheet Summary of Hydraulic Conductivity Tests

Appendix C – Slug Test Analyses

Appendix D – Pump Test Analyses

APPENDIX C

PROPOSED PHASE II WORK PLAN

DEMONSTRATION/VALIDATION OF LONG-TERM MONITORING USING WELLS INSTALLED BY DIRECT PUSH TECHNOLOGIES

APPENDIX C

PROPOSED PHASE II WORK PLAN

DEMONSTRATION/VALIDATION OF LONG-TERM MONITORING USING WELLS INSTALLED BY DIRECT PUSH TECHNOLOGIES

1/30/02

NFESC Codes 414/411

Mark Kram

William Major

Dale Lorenzana

Thomas Strassburger

Team Members/Site Leaders:

Chris Antworth:	**Tyndall Air Force Base**
William Major:	**Port Hueneme National Test Site**
Tim McHale:	**Dover National Test Site**
Louise Parker:	**Cold Regions Research Engineering Laboratory**

TABLE OF CONTENTS

	Page
BACKGROUND	3
PHASE I DESCRIPTION AND STATUS	4
Sampling and Laboratory Analyses	4
Statistical Data Analyses	5
Specific Challenges	7
PHASE II PROPOSED EFFORT	7
Specific Tasks for Each Site	10
Certification Efforts	13
REFERENCES	14

FIGURES

Figure 1. General Map of Well Locations at CRREL.

Figure 2. Map of DNETTS showing locations of all CPT-installed monitoring wells.

Figure 3. Cell B Well Cluster Configuration, PHNETTS.

Figure 4. Cell B Layout, PHNETTS.

Figure 5. General Map of Well Locations at TAFB.

Figure 6. Proposed Phase II CRREL Well Location Map.

Figure 7. Proposed Phase II DNETTS Well Location Map.

Figure 8. Proposed Phase II PHNETTS Well Location Map.

IMAGES

Image 1. Proposed Phase II DNETTS Well Locations, Cluster 235D.

Image 2. Proposed Phase II DNETTS Well Locations, Cluster 237S.

Image 3. Proposed Phase II DNETTS Well Locations, Cluster 337S.

Image 4. Proposed TAFB Well Locations, Cluster MW9

Image 5. Proposed TAFB Well Locations, Cluster T65.

APPENDICES

Appendix 1. Well Construction Details

Appendix 2. Prioritized List of Advisory Committee Comments and Recommendations, December 2001

BACKGROUND

The purpose of the Long Term Monitoring (LTM) project is to determine whether significant statistical differences exist between long term ground water monitoring results obtained from wells installed by two different methods. Direct push (DP) well designs are compared to a baseline of conventional Hollow Stem Auger (HSA) drilled wells. There are thousands of DoD hazardous waste sites with anticipated cleanup and monitoring requiring billions of dollars. Currently, long-term monitoring of contaminants typically includes installation of wells with conventional HSA methods. Costs for well installation typically represent a significant portion of the allocated remediation and monitoring budget. Cost reductions through improved well installation techniques could be significant, especially when initial penetrometer site characterization efforts are coupled to well installation tasks in the same deployment. Direct-push wells are not typically accepted for long-term monitoring applications, since an unequivocal comprehensive evaluation has not been previously conducted. Therefore, there is a need to evaluate whether these cost-effective devices are reliable for long-term solute monitoring applications. If so, there must be a simultaneous effort to convince the regulatory community of the validity of the study through a regulatory certification process.

Comparison tests have been conducted at five selected sites on military installations with documented dissolved phase contaminants. Phase I of the study has been completed and is briefly described in the following section. For Phase II, the main goals are as follows:

- identify shortcomings in the Phase I efforts;
- consult with regulatory representatives and leading industry experts to articulate specific experimental design constraints required to achieve regulatory acceptance for direct push well installation methods;
- generate a revised Work Plan;
- implement the revised Work Plan;
- facilitate direct push well technology transfer; and
- complete the technology certification process.

PHASE I DESCRIPTION AND STATUS

Sampling and Laboratory Analyses

Monitoring wells located at the U.S. Army Cold Regions Research Engineering Laboratory (CRREL), Dover National Environmental Technology Test Site (DNETTS), Hanscom Air Force Base (HAFB), Port Hueneme National Environmental Technology Test Site (PHNETTS), and Tyndall Air Force Base (TAFB) were studied during the Phase I investigation. For CRREL, DNETTS, Hanscom, and Tyndall, new direct push wells were installed adjacent to existing conventional wells. GeoProbe Systems, Inc. installed three ½-inch diameter pre-packed PVC direct-push wells adjacent to three existing 4-inch diameter PVC wells at CRREL (Figure 1). At DNETTS, six 2-inch diameter direct-push wells were installed adjacent to existing 2-inch diameter conventional wells (Figure 2) using DNETTS's trailer mounted cone penetrometer test (CPT) rig. Four clusters of five different well types were installed at PHNETTS (Figures 3 and 4), including different configurations of ¾-inch and 2-inch diameter wells, some with prepacked screens and some without. Each cluster included one conventional well, installed with a HSA rig, and four direct-push designs, installed with a Precision hydraulic push rig. Two different styles of direct-push wells were installed at Tyndall, creating six clusters of three different styles of wells (Figure 5). Six 1 ½-inch diameter wells were installed utilizing the Army Corps of Engineer's CPT rig, and six ½-inch diameter wells were installed using a GeoProbe system. Well construction details are presented in Appendix 1 of the Quarterly Progress Report (1) and the NFESC Technical Report (2). Selected details are summarized in Appendix 1 of this work plan. Note that organic analytes under consideration consist of halogenated compounds, fuel compounds, and methyl tertiary butyl ether (MTBE).

From October 2000 to November 2001, five (5) groundwater-sampling events were completed at four of the five LTM sites. The exception was CRREL, where limitations of the ½-inch pump at the target sample depth (approximately 125 feet bgs) have prevented sample collection. Laboratory analyses were conducted to determine contamination levels for fourteen groundwater solutes of concern including MTBE, BTEX, TCE, DCE, vinyl chloride (VC), and chlorobenzene as well as seventeen inorganic constituents used in monitored natural attenuation approaches. In addition, seven physical and chemical parameters were measured before and during the well purging procedure. Low flow sampling procedures were used throughout the study.

The Applied Research Associates *Quarterly Progress Report: Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct Push Technologies*, dated 16 April 2001, describes efforts completed as of April, 2001 (1). The report consists of descriptions of project scope, well installation efforts, sampling efforts, descriptions of the draft ASTM standards, Port Hueneme slug test description, statistical analyses, as well as a discussion of the preliminary results. A 2nd fiscal quarterly report describing statistical analyses of the comparison results-to-date and slug tests was released on 16 November 2001 (3).

Statistical Data Analyses

In anticipation of future efforts, our team performed new statistical comparisons on an analyte-by-analyte basis for each of the sites. This was conducted based on a consensus of government and university statisticians. Results are described as follows:

For the Dover and Hanscom sites, the data or log data was tested for normality, and then the appropriate paired-t test (on the data or log-data) or Wilcoxan Signed Rank test was performed. For the Tyndall and Port Hueneme sites, after testing the data (or log data) for normality, the appropriate One-way Repeated Measures ANOVA test (RM-ANOVA) or the Friedman One-way RM-ANOVA on Ranks test was performed. At Port Hueneme, the two sites were treated separately because of the difference in the number of wells in each of the clusters (3 vs. 5). Statistical analyses were conducted only on analytes where there was sufficient data for comparison.

For the Dover site, there were no significant differences between the 2-inch HSA (with conventional sand pack) and 2-inch DP (with no pre-pack) wells for Total Dissolved Solids, Total Hardness, or any of the organic analytes that were compared, including benzene (BENZ), cis-1,2-dichloroethylene (CDCE), trichloroethylene (TCE), tetrachloroethylene (PCE), trichloroethane (TCA), o-xylene (OXYL), and methyl-tert-butyl-ether (MTBE).

Similarly, at the Hanscom site, there were no significant differences between the 4-inch HSA well (conventional sand pack) and the ½-inch DP well (quasi-static installation, with pre-pack) for Total Dissolved Solids, Total Hardness, or any of the VOCs that were compared (CDCE, OXYL, PLCB, and TCE).

At Tyndall Air Force Base, concentrations of TCE, BENZ, and OXYL were significantly higher in the 1.5-inch DP wells (with no-pre-pack) than in the 2-inch HSA wells (with conventional sand pack). Also of interest, concentrations of TCE and OXYL were significantly higher in the ½-inch DP wells (with pre-pack) than in the 2-inch HSA wells, and concentrations of ethylbenzene were significantly higher in the 1/2-inch DP wells than the 1.5-inch DP wells.

There were no significant differences between any of the well types for Total Hardness or Total Dissolved Solids at either site A or B at Port Hueneme. At site A, concentrations of MTBE were significantly higher in the ¾-inch DP wells (ASTM designed) than in the 2-inch HSA wells (ASTM designed). There was no significant difference between the concentrations of MTBE in the 2-inch ASTM designed HSA or DP wells. At site B, the only significant difference in MTBE concentrations in any of the five well types were between the 2-inch HSA and the 2-inch DP wells. Again, concentrations were higher in the DP well.

To differentiate sources of data variability, triplicate sampling was performed for all Port Hueneme sampling events. The variance within the triplicate samples was found to be very low therefore inferring that the well sample extraction method and subsequent storage, transport and lab analysis had no significant contribution to data variability. With the low variance in the triplicates and the ANOVA results showing mostly no significant differences between wells types, it is most likely that variability exhibited in the raw data is primarily due to the spatial heterogeneity of the analytes in the soil and temporal differences. We anticipate that at the other sites variability among multiple samples collected from each well will prove to be low (implying that we can be assured of a sound assessment of spatial heterogeneity). Therefore, we plan to discontinue the triplicate sampling requirement in all Phase II sampling events, but will continue to collect and analyze appropriate QA/QC samples.

In conclusion, we have found no significant difference at any of the sites for the inorganic parameters such as Total Dissolved Solids and Total Hardness. In general, concentrations of VOCs have not been significantly different for the DP wells and conventional wells. Where significant differences do occur, concentrations have been higher in the DP wells. This data indicates that DP wells are reliable and conservative in representing contamination at a site. While the power (or likelihood that you will identify a significant difference when one exists) of the statistical tests is reasonable for some of our comparisons, it is low for others, implying that our conclusions regarding well performance is not yet strong. We therefore plan to collect

additional sampling rounds from each well in the study. Once completed with a sufficient number of data points, a power of the tests can be determined to support or refute implications associated with the statistical results. Furthermore, there is a need to compare HSA wells to other nearby identically designed HSA wells to better understand the variability within the solute concentration distribution. Therefore, we plan to install new HSA wells in selected clusters, and to compare the HSA-HSA variability with that observed between the HSA and direct-push designs.

Specific Challenges

Although analyte concentrations in soils are typically heterogeneous, it has been observed that the *degree* of variability fluctuates significantly for each analyte. Primary factors are believed to be varied sorption of analytes to soil particles and low hydrodynamic dispersion (or mixing) of analytes in vertical and lateral directions leading to steep concentration gradients. For instance, order-of-magnitude changes in several organic solute concentrations can be observed over very small (sub-meter) distances. As discussed, Phase II efforts will address these analyte variability issues by increasing statistical power through sample repetition and by determining the HSA-HSA variability.

Efforts to date at CRREL to recover samples from the deep (approximately 125 ft bgs) wells have proven challenging. Phase II efforts will therefore include installation of a slightly larger diameter direct push design to facilitate the use of pumps capable of yielding representative samples at flow rates and depths of interest.

PHASE II PROPOSED EFFORT

On 13 and 14 December 2001 an advisory committee consisting of federal regulatory, academia and remediation consulting experts with regard to monitoring well technology and geostatistical analyses participated in a workshop specifically designed to address the concerns related to this project. The committee reviewed all Phase I results and proposed necessary changes in the Phase II experimental design. Appendix 2 includes a list of prioritized advisory committee comments and names and brief backgrounds for the committee members and regulatory participants. Based on these comments, the Phase II proposed recommendations and comments will be incorporated as follows:

1) The current well data set collected at five DOD sites over the last 18 months is of excellent quality and can be used to its full potential for well comparison statistical analyses. However, previous statistical data analyses conducted by the contractor were inaccurate because the data set had been confounded by combining the data for different types of DP wells from the various sites into one data set. This method of analysis does not allow for quantification of the spatial and temporal components of variability. As discussed in the previous section entitled "Statistical Data Analyses", the statistical method has been modified so that all analyses are conducted on a site-by-site and analyte-by-analyte basis. Solute concentrations will be compared using standard t-Tests on the data or log data or Wilcoxon Paired Rank Sum tests and ANOVA tests on the data or log data or an ANOVA on the ranked data (as appropriate, depending on the normality of the data). ANOVA analyses will allow us to determine external (non-well type) factors controlling observed variability and whether performance of the different well types is consistent;

2) In order to meet the advisory committee recommendations for the duration of the study, it is proposed that during Phase II we conduct a total of (8) eight quarterly sampling events for organic analytes over a two-year period. Phase II sampling events are also essential to increase the statistical power of current and future data sets. Sampling events will be scheduled to incorporate observations through seasonal changes. Randomized single aliquot samples will be collected for all rounds. Sampling for monitored natural attenuation inorganics and metals will be conducted only in the third quarters of FY02 and FY03;

3) To augment sites with limited hydrogeologic data, a complete hydrogeologic characterization data set including soil type, grain size distribution, permeability, and hydraulic conductivity will be generated during Phase II well installations;

4) To determine HSA:HSA variability, a few additional HSA wells will be installed and monitored for specific clusters. Currently, there exists one HSA well in each cluster of 1 to 4 DPT wells at all test sites. Although the single HSA well currently serves as a control for comparing all DPT wells, addition of a second HSA well will help demonstrate the potential variability between HSA wells for any given sampling event. If the concentration variability between HSA wells is greater than or comparable to the variability expressed in the comparisons with DPT wells, this could support claims that DPT wells are comparable in performance. It is recommended that we continue to use the original HSA wells as controls;

5) To substantiate the evaluation of different types of DP wells, selected well pairs will be converted into clusters similar to those currently used at the Port Hueneme site. Figures 6 through 8 and Images 1 through 5 display the new proposed well configuration for each test site.

6) To gain regulatory acceptance, CalEPA certification will be pursued. Additional direct push well studies and efforts (listed below) will also be integrated into this process.
   a) ITRC Sampling, Characterization and Monitoring group case study,
   b) EPA Direct Push Working group,
   c) USAF/Parsons study of data from existing pushed wells (USAF Cleanup Technology Workshop),
   d) ASTM direct push well guidance;

7) An expert advisory panel will be maintained to insure that the best approach and methods are used in this study. In addition, the involvement of these experts will be instrumental in obtaining credibility within the regulatory community overseeing future certification and guidance efforts;

8) The services of a spatial statistician versed in the area of geochemical assessment will be maintained to support the development of the Phase II work plan and to interpret raw analytical data.

Additional considerations include the following:

- Our current study does not include a test site with metals contaminants. This may be required to satisfy regulatory concerns. However, the Advisory Committee feels that measurement of selected inorganic constituents at our current sites may be sufficient to claim that direct-push well designs would perform appropriately at metals contaminant sites.
- This Draft Work Plan was generated prior to receipt of California certification requirements. Upon receipt of our proposed work plan and existing database, specific modifications may be required to meet criteria set forth in the certification program.

Specific Tasks for Each Site:
Each of the current sites will undergo changes in the overall management of monitoring efforts and sampling frequencies. These changes are briefly discussed below.

<u>CRREL (Site Leader: Louise Parker)</u>

Characterization:

Advance piezocone for continuous soil type logging; collect soil samples every 2.5' throughout the proposed screen zones; determine grain size distribution for each soil sample; determine appropriate ASTM filter pack recommendation for each screened zone based on grain size distribution; analyze soils for analytes of interest; analyze water using direct push sample collection every 2.5' throughout proposed screen zone; conduct pneumatic slug tests prior to and following development of all new wells.

Well Installation:

Because the depth of the CRREL wells has pushed the limits of the currently existing ½-inch pump technology, we recommend adding one 3/4" diameter hammer installed pre-pack DP well to three selected pairs (CECRL 9, 10, and 11), screened to the same depth as the 4" drilled wells; develop well. We anticipate that installation will not be a problem because the same rods that were used to install the ½-inch wells will be used to install the ¾-inch wells and there are more 3/4-inch pumps to select from.

Monitoring:

Monitor each well as single aliquots (organics and inorganics through 8 quarterly rounds); monitor an additional 10% for quality control. Analyze for pre- and post-development turbidity. If post-development turbidity of new well is much lower than older wells (greater than 20% difference), re-develop older wells. If siltation is extreme in old wells (e.g., screened intervals silted), it will be removed. Inorganics monitored as single aliquots. CRREL water is very corrosive, and we expect this could be one site where we may see a difference in iron levels due to corrosion of stainless steel.

<u>Dover NETTS (Site Leader: Tim McHale)</u>

Characterization:

Advance piezocone for continuous soil type logging; collect soil samples every 2.5' throughout the proposed screen zones; determine grain size distribution for each soil sample (in field); determine appropriate ASTM filter pack recommendation for each screened zone based on grain size distribution; analyze soils for analytes of interest; analyze water using direct push sample collection every 2.5' throughout proposed screen zone; conduct pneumatic slug tests prior to and following development of all new wells.

Well Installation:
Two individual well designs will be added to two existing well pairs in three separate locations, two chlorinated hydrocarbon locations (Clusters 235D and 237S) and one MTBE cluster (337S). Specifically, the following well designs will be installed to generate 3 separate clusters:

- one additional 2"-diameter ASTM specified drilled well (same screen length as original (10'));
- one additional 3/4"-pushed pre-pack well (10' screen);

Monitoring:
Monitor each well as single aliquots (organics through 8 quarterly rounds and inorganics through 2 quarterly rounds); monitor an additional 10% for quality control. Analyze for pre- and post-development turbidity. If turbidity of new wells is much lower than older wells (greater than 20% difference), re-develop older wells. If siltation is extreme in old wells (e.g., screened intervals silted), it will be removed.

Port Hueneme NETTS (LTM Site Leader: William Major)
Site Characterization:
Characterization is relatively complete. Additional characterization (boring logs, etc.) will be generated during installation of new well. Pneumatic slug tests will be conducted for selected wells.

Well Installation:

One additional well design will be added to five wells currently present in each of two selected clusters (total of two additional wells), each placed on opposite side of cluster (e.g., towards SE) from original drilled well:

- one additional 2”-diameter ASTM specified drilled well (for two clusters; one 2’ screen (Cluster B1) and one 5’ screen (Cluster B4)).

Monitoring:

Monitor each well as single aliquots (organics through 8 quarterly rounds and inorganics through 2 quarterly rounds); monitor an additional 10% for quality control. Analyze for pre- and post-development turbidity. If turbidity of new well is much lower than older wells (greater than 20% difference), re-develop older wells. If siltation is extreme in old wells (e.g., screened intervals silted), it will be removed. There currently exists a 7-depth multi-level well and a single 12’ screen 3/4”-pushed hammer probe no-pack well adjacent to Cluster B4. For at least two events, collect and analyze samples from the multi-level well adjacent to Cluster B4.

<u>Tyndall AFB (Site Leader: Chris Antworth)</u>

Characterization:

Advance piezocone for continuous soil type logging; collect soil samples every 2.5’ throughout the proposed screen zones; determine grain size distribution for each soil sample; determine appropriate ASTM filter pack recommendation for each screened zone based on grain size distribution; analyze soils for analytes of interest; analyze water using direct push sample collection every 2.5’ throughout proposed screen zone; conduct pneumatic slug tests prior to and following development of all new wells.

Well Installation:

Two individual well designs will be added to four wells designs currently present in two separate locations (Cells MW9 and T65) to create two clusters of six wells each. Specifically, the following well designs will be installed to the two selected clusters:

- one additional 2”-diameter ASTM specified drilled well (same screen length as original (10’)); and
- one additional 1.5”-pushed no-pack well with a screen length commensurate with others in the clusters (approximately 10’).

Monitoring:

Monitor each well as single aliquots (organics through 8 quarterly rounds and inorganics through 2 quarterly rounds); monitor an additional 10% for quality control. Analyze for pre- and post-development turbidity. If turbidity of new wells is much lower than older wells (greater than 20% difference), re-develop older wells. If siltation is extreme in old wells (e.g., screened intervals silted), it will be removed.

Certification Efforts

The ESTCP Long-Term Monitoring team is currently working towards several direct-push technology certifications. Preliminary efforts have been initiated to obtain California EPA certification of DP installed wells using this project and data solicited from external concurrent studies. In order to streamline the certification process, the team members will work with members of the regulatory community to identify and articulate specific steps required for addressing each of the certification criteria. Discussion of critical issues has already been initiated. Specific steps addressing regulatory concerns have been incorporated into the proposed tasks for each site discussed above. Each of these steps will be incorporated into the final work plan for field implementation. A timeline for specific deliverables will be generated and agreed upon by members of the collaborating entities. The ultimate goal is to obtain regulatory certification for the use of direct-push installed monitoring wells for long term monitoring.

In a parallel efforts, the LTM team will continue to work with the ITRC panel for Sampling, Monitoring and Characterization (SMC) and will aggressively pursue acceptance of DP installed wells for appropriate sites. We will be formally presenting the ESTCP direct-push well project and hosting the next SMC meeting at NFESC, Port Hueneme in June 2002. Additionally, ASTM team members (e.g., J. Shinn, S. Farrington, L. Parker) are currently generating two direct-push well standards. *Standard Practice for Direct Push Installation of Prepacked Screen Monitoring Wells in Unconsolidated Aquifers* and *Standard Guide for Selection and Installation of Direct Push Ground Water Monitoring Wells* have been accepted at society level and are currently being finalized.

REFERENCES

[1]ARA, 2001a. Quarterly Progress Report: Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct Push Technologies, April, 2001.

[2]Kram, Mark L., Dale Lorenzana, Joel Michaelsen, and Ernest Lory, 2001. Performance Comparison: Direct-Push Wells Versus Drilled Wells, NFESC Technical Report, TR-2120-ENV; http://enviro.nfesc.navy.mil/erb/erb_a/restoration/technologies/invest/access_tools/tr2120_wells.pdf.

[3]ARA, 2001b. Quarterly Progress Report: Demonstration/Validation of Long-Term Monitoring Using Wells Installed by Direct Push Technologies, November, 2001.